Methoden zur Abschätzung extremer Hochwasser

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Guido Felder

von Schüpfheim

Leiter der Arbeit:

Prof. Dr. R. Weingartner

Geographisches Institut der Universität Bern

Urheberrechtlicher Hinweis

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Der Dekan:
Bern, 2. Juni 2016
Prof. Dr. G. Colangelo

Zusammenfassung

Abschätzungen für extreme Hochwasser quantifizieren je nach Definition äusserst seltene Ereignisse ($HQ_{10\,000}$), oder gar das vermutete maximal mögliche Hochwasser (Probable Maximum Flood, PMF). Das Verständnis der in diesem Fall ablaufenden Prozesse ist aufgrund fehlender Referenzereignisse stark eingeschränkt, und für vorgenommene Schätzungen gibt es keine direkten Validierungsmöglichkeiten. Die Abschätzung extremer Hochwasser stellt deshalb eine grosse Herausforderung dar, und die dabei angewandten Methoden bedürfen einer ständigen Weiterentwicklung und Evaluation. In der vorliegenden Arbeit werden zwei Teilaspekte der PMF-Hochwasserabschätzung vertieft behandelt: Die räumlich-zeitliche Verteilung eines Extremniederschlages, und die Herleitung eines PMF-Hochwassers aus dem Extremniederschlag mittels Niederschlag-Abfluss-Modellierung.

Der ersten Teil der vorliegenden Arbeit beinhaltet ein neues Verfahren zur räumlich-zeitlichen Verteilung des vermuteten maximal möglichen Niederschlages (Probable Maximum Precipitation, PMP). Der vorgestellte Monte-Carlo-Ansatz ermöglicht die Herleitung einer Vielzahl unterschiedlicher Niederschlagsverteilungen unter Berücksichtigung physikalischer Plausibilitätskriterien, und schliesslich die Identifikation der folgenreichsten, sprich hochwassermaximierenden räumlich-zeitlichen Verteilungen. Die Resultate zeigen auf, dass sich ein Monte-Carlo-Ansatz zur Identifikation von worst-case-Szenarien eignet. Zusätzlich erlaubt die Anwendung des Verfahres eine erste grobe Abschätzung des PMF-Hochwassers.

In einem zweiten Teil wird aus den generierten Niederschlagsszenarien ein PMF-Hochwasser abgeschätzt. Dabei kommen zwei verschiedene Modellierungsansätze zur Anwendung: Ein deterministisches hydrologisches Modell und ein gekoppeltes hydrologisch-hydraulisches Modell. Die Resultate belegen, dass eine Kopplung von hydrologischen und hydraulischen Modellen im Vergleich zur herkömmlichen hydrologischen Modellierung eine dämpfende Wirkung auf die modellierte PMF-Schätzung hat. Für die Abschätzung von Hochwasserereignissen, welche die Bemessungsgrössen von Schutzbauten entlang des Gerinnes womöglich deutlich übertreffen, bringt die damit einhergehende Berücksichtigung grossflächiger Überflutungs- und Retentionsräume einen deutlichen Mehrwert.

In den letzten Jahren sind im wissenschaftlichen wie auch im privatwirtschaftlichen Umfeld zahlreiche PMF-Abschätzungen vorgenommen worden. Die gewählten Methoden zur räumlich-zeitlichen Repräsentierung des PMP-Niederschlages und zur anschliessenden Modellierung sind dabei sehr unterschiedlich. Die Wahl der Methoden kann jedoch einen relativ grossen Einfluss auf die resultierende Abschätzung haben. Im dritten Teil der Arbeit werden verschiedene Methoden zur räumlich-zeitlichen Niederschlagsverteilung und verschiedene Modellierungsansätze hinsichtlich ihrer Eignung für die Abschätzung des PMF-Hochwassers systematisch getestet. Die Resultate zeigen auf, dass die Wahl der Methode zur räumlich-zeitlichen Niederschlagsverteilung und die Wahl des Modellierungsansatzes aufeinander abgestimmt sein müssen, um eine markante Über- oder Unterschätzung des PMF-Hochwassers zu vermeiden.

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1 Einleitung

Naturgefahren können mit einer unendlichen Zahl von Szenarien beschreiben werden. Manche dieser Szenarien sind wahrscheinlicher als andere, und die meisten dieser Szenarien werden vermutlich in absehbarer Zeit nicht eintreten. Aufgrund der Vielfalt an Möglichkeiten ist ein Schutz vor allen Szenarien, und damit ein absoluter Schutz vor Naturgefahren, nicht realisierbar. Die der Gesellschaft zur Verfügung stehenden Möglichkeiten bewegen sich zwischen maximalem Schutz vor Naturgefahren und keinem Schutz vor Naturgefahren. Der erstrebenswerte Grad des Schutzes zwischen diesen beiden Extremen wird in der Regel in einem gesellschaftlichen Diskurs ausgehandelt. Dabei muss sowohl im Allgemeinen wie auch im konkreten Einzelfall die Frage beantwortet werden, welche Schutzmassnahmen realisiert und finanziert werden sollen. Im Umkehrschluss bedeutet das auch einen Diskurs über die Frage, welches Restrisiko als akzeptierbar angenommen wird. Dieser Ansatz zur Festlegung des erwünschten Schutzes vor Naturgefahren bildet eine Grundlage des integralen Risikomanagements, wie es in der Schweiz angewendet wird (BABS, 2014).

1.1 Relevanz von Extremhochwasserabschätzungen

Bei der Planung und Realisierung von Schutzmassnahmen im Rahmen des integralen Risikomanagements findet in der Regel eine Abwägung zwischen Kosten und Nutzen einer Schutzmassnahme und dem akzeptierbaren Restrisiko statt („integrale Risikobewertung“ nach BABS (2014)). Im aktuellen Diskurs geht das akzeptierbare Restrisiko für besonders folgenreiche Naturrisiken gegen Null. Das bedeutet, dass in solchen Fällen der Schutz auch gegen Szenarien mit sehr kleinen Eintretenswahrscheinlichkeiten, oder sogar gegen alle denkbaren Szenarien, gewährleistet sein muss. Dies umfasst beispielsweise die Gefährdung nuklearer Kraftwerke, wofür die Gesetzgebung momentan den Schutz gegen Hochwasser mit einer Wiederkehrperiode von 10^4 Jahren vorsieht. Die Gesetzgebung macht allerdings keinerlei Angaben dazu, wie und anhand welcher Methoden ein Hochwasser dieser Wiederkehrperiode bestimmt werden soll.

Naturkatastrophen können für alle Teile der Gesellschaft folgenreich sein, so auch für juristische Personen. Besonders auf die Versicherungsindustrie können die finanziellen Auswirkungen eines Extremereignisses gravierend ausfallen. Durch gesetzliche Vorgaben sind Versicherungen in der Schweiz dazu verpflichtet, im Falle eines Extremereignisses die versicherten Schäden decken zu können, sei dies durch die Rückstellung von Eigenmitteln oder durch den Abschluss von Rückversicherungen. Dies bedarf einer möglichst genauen Abschätzung sehr seltener Gefahren. Ist die Abschätzung von Gefahren zu optimistisch, können im Eintretensfall womöglich nicht alle versicherten Schäden gedeckt werden. Im Falle einer zu pessimistischen Abschätzung sind die Rückstellungen beziehungsweise die Rückversicherungsprämien unverhältnismässig hoch. Weiter sind auch Rückversicherer an einer fundierten Schätzung interessiert. Dies einerseits, um im Eintretensfall genügend liquide Mittel bereitstellen zu können, und andererseits, um die Höhe der Rückversicherungsprämien festzulegen.

1.2 Methodenüberblick

An dieser Stelle wird ein allgemeiner Überblick über die gängigen Methoden und Ansätze zur Abschätzung von Extremhochwassern gegeben. Eine detailliertere Darstellung des aktuellen Standes der Forschung in jedem Teilbereich, sowie eine diesbezügliche Einordnung der entsprechenden Teilstudien, ist in den jeweiligen Kapiteln separat enthalten.

In der vorliegenden Arbeit gelten extreme Hochwasser als sehr seltene Ereignisse, deren Abflussspitzen im Bereich der oberen Grenze der physikalischen Plausiblität liegen. Für Abschätzungen in diesem Bereich kann grundsätzlich zwischen statistischen und deterministischen Methoden unterschieden werden. Mit statistischen Methoden werden Extremereignisse anhand von Eintretenswahrscheinlichkeiten klassifiziert, wie zum Beispiel die erwähnte Wiederkehrperiode von 10^4 Jahren, was einer jährlichen Eintretenswahrscheinlichkeit von 10^{-4} entspricht ($HQ_{10\,000}$). Die Herleitung eines worst-case-Ereignisses dagegen beruht in der Regel auf der Anwendung deterministischer Methoden. In der Praxis wird die Abschätzung eines Ereignisses mit einer Wiederkehrperiode von 10^4 Jahren und die Abschätzung des worst-case-Ereignisses aufgrund methodischer Schwierigkeiten und relativ grosser Unsicherheiten häufig komplementär verwendet (z.B. in ENSI (2013)).

1.2.1 Statistische Methoden

Bei den statistischen Methoden wird der zu schätzende Wert, meist die Hochwasserspitze eines Kalenderjahres, als Zufallsvariable aufgefasst. Aus den gemessenen Jahreshochwasserspitzen HQa wird eine empirische Verteilungsfunktion der HQa abgeleitet, welche dabei als Beschreibung der Verteilung der Grundgesamtheit der HQa herangezogen wird. Aus der empirischen Verteilungsfunktion der HQa wird so jeder Hochwasserspitze eine Wiederkehrperiode zugewiesen. Umgekehrt kann einer beliebigen Wiederkehrperiode eine Hochwasserspitze zugewiesen werden (Maniak, 2005).

Sowohl theoretische Experimente als auch Erfahrungen aus praktischen Anwendungen dieses Konzepts haben gezeigt, dass eine seriöse Schätzung nur für einen Extrapolationsbereich gemacht werden kann, welcher das zwei- bis dreifache der Messreihenlänge umfasst (Coles, 2004; DWA, 2012). Verschiedene Ansätze erlauben es jedoch, die Stichprobengrösse und damit den Extrapolationsbereich zu vergrössern (DWA, 2012): Die zeitliche Informationserweiterung umfasst im Wesentlichen den Einbezug von Informationen über historische Hochwasser im entsprechenden Einzugsgebiet (Hosking und Wallis, 1986; Macdonald u. a., 2014; Schumann, 2007). Die kausale Informationserweiterung umfasst den Einbezug von Informationen aus physiogeographisch ähnlichen Einzugsgebieten (Haddad und Rahman, 2012; Zaman u. a., 2012; Smith u. a., 2015). Weiter kann die Stichprobe durch die Anwendung stochastischer Wettergeneratoren (Semenov, 2008) oder durch resampling von Wetterdaten (Paquet u. a., 2013) und anschliessender hydrologischer Modellierung der erzeugten Daten vergrössert werden.

Die Anwendung statistischer Methoden setzt jedoch gemäss DWA (2012) unter anderem eine Stationarität des Einzugsgebietes voraus. Gerade bei grossen Extrapolationszeiträumen ist diese unter anderem aus folgenden Gründen nicht immer gegeben:

- Die Abflussbildung in einem Einzugsgebiet kann sich im Laufe eines Hochwasserereignisses deutlich verändern. Laut Rogger u. a. (2012) geschieht dies hauptsächlich aufgrund räumlich variierenden Bodenspeicherkapazitäten in einem Einzugsgebiet. Dieser Effekt kann eine extremwertstatistische Extrapolation massgeblich beeinflussen (Rogger u. a., 2012).

- Im Laufe eines Hochwasserereignisses werden mit zunehmendem Abfluss in unregelmässigen Abständen neue Überflutungsflächen erschlossen. Die Erschliessung eines grossräumigen Überflutungsbereiches führt zu einer vorübergehenden Speicherung eines bestimmten Abflussvolumens, zu einer Verlangsamung des Abflussprozesses und schliesslich zu einer Abminderung der Hochwasserspitze in unterliegenden Gebieten. Dieser Effekt ist vor allem bei extremen Hochwassern ausgeprägt, da in einem solchen Fall weiträumige Gebiete überflutet werden können (Naef und Thoma, 2010).

- Klimatische Variationen während der Beobachtungsperiode haben einen Einfluss auf die Häufigkeit und Intensität der Hochwasser. Die Verteilung der Grundgesamtheit ist nicht über Jahrzehnte hinweg stabil, wodurch vor allem ältere Messwerte nicht unbedingt Repräsentativ für die Abschätzung heutiger Hochwassereintretenswahrscheinlichkeiten sein müssen (Ward u. a., 2011).

- Durch anthropogene Einflüsse im Einzugsgebiet, wie zum Beispiel Landnutzungsänderungen (Waldwuchs, Bodenversiegelung, etc.), oder durch wasserbauliche Eingriffe kann sich die Einzugsgebietsreaktion im Laufe der Zeit verändern.

In zahlreichen Fallstudien wurde versucht, die Instationarität in der Extremwertanalyse zu berücksichtigen (Beguería u. a., 2011; Hundecha u. a., 2008; López und Francés, 2013; Silva u. a., 2014; Villarini u. a., 2009). Nicht-stationäre Ansätze erlauben es theoretisch, klimatische Variationen und anthropogene Einflüsse auf die Eintretenswahrscheinlichkeit von Hochwassern zu Berücksichtigen. Die methodische Zulässigkeit solcher Ansätze wird kontrovers diskutiert (Sivapalan und Samuel, 2009; Salas u. a., 2014; Serinaldi und Kilsby, 2015). Die Qualität und der Mehrwert dieser Methoden für die extremwertstatistische Hochwasserabschätzung ist aufgrund relativ grosser Unsicherheiten umstritten.

Aus diesen Gründen ist die Aussagekraft einer statistischen Hochwasserabschätzung im Bereich sehr geringer Wahrscheinlichkeiten, trotz vergrösserter Stichprobe durch Miteinbezug von historischer und kausaler Informationserweiterung, und trotz dem Einsatz immer komplexerer statistischer Modelle, grundsätzlich eingeschränkt. Der maximale Schutz sensitiver Infrastruktur bedingt daher eine ergänzende Abschätzung mittels deterministischer Methoden.

1.2.2 Deterministische Methoden

Die Abschätzung eines worst-case-Ereignisses kann mittels deterministischer Methoden vorgenommen werden. Im Gegensatz zu den statistischen Ansätzen wird hierbei dem Parameter von Interesse (in der Regel der Spitzenabfluss oder das Abflussvolumen) keine Wahrscheinlichkeit zugeordnet, sondern seine physikalische Obergrenze abgeschätzt. Dies geschieht in zwei Schritten: Zuerst wird der vermutlich maximal mögliche Niederschlag („Probable Maximum Precipitation“, PMP) abgeschätzt, anschliessend wird daraus das vermutlich maximal mögliche Hochwasser („Probable Maximum Flood“, PMF) abgeleitet.

Probable maximum precipitation PMP

Für den PMP-Niederschlag existieren mehrere Definitionen, welche sich in ihrer Aussage jedoch wenig voneinander unterscheiden (vgl. Salas u. a., 2014). Am weitesten verbreitet ist die Definition der Weltorganisation für Meteorologie (WMO), nach welcher sich auch die vorliegende Arbeit richtet. Sie lautet:

> “PMP is the theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year.“
> WMO (2009)

Für die Abschätzung des PMP-Niederschlages existieren zahlreiche Ansätze, welche in einem Handbuch der Weltorganisation für Meteorologie ausführlich beschrieben sind (WMO, 2009). Die Grundidee dieser Abschätzung ist es, den maximalen Feuchtegehalt der

Atmosphäre sowie die maximale Feuchtezufuhr über einem Einzugsgebiet zu approximieren, und daraus maximal mögliche Niederschlagsmengen abzuleiten. Als Ausgangspunkt dafür dient jeweils der Zustand der Atmosphäre während verschiedenen gemessenen Niederschlagsereignissen. Eine solche Abschätzung des PMP-Niederschlages basiert demnach auf gemessenen Zuständen der Atmosphäre und ist damit zu einem bestimmten Grad abhängig von der Verfügbarkeit und Qualität von Messreihen. Eine unzureichende Datengrundlage hat in einzelnen Fällen dazu geführt, dass die theoretisch hergeleitete Obergrenze erreicht oder überschritten wurde (Dawdy und Lettenmaier, 1987; Koutsoyiannis, 1999). Solche Fälle haben zur Entwicklung weiterer PMP-Abschätzmethoden motiviert, allen voran zu statistischen Methoden nach Hershfield (1965) und Koutsoyiannis (1999).

Als Konsequenz aus diesem methodischen Disput unterscheiden Salas u. a. (2014) zwischen einem theoretischen PMP-Niederschlag, welcher die obere Grenze des möglichen Niederschlages bildet und definitionsgemäss keine Überschreitungswahrscheinlichkeit aufweist, und einem praktischen PMP-Niederschlag, bei dem die Abhängigkeit von gemessenen Daten berücksichtigt wird und welchem extremwertstatistisch eine Überschreitungswahrscheinlichkeit zugewiesen werden kann. Der Mehrwert einer Zuweisung einer Überschreitungswahrscheinlichkeit zu einem PMP-Niederschlag, welche charakteristisch in der Grössenordnung von $p=10^{-5}$ bis 10^{-7} zu liegen kommt, gegenüber einer Abschätzung des PMP-Niederschlages im Sinne einer physikalischen oberen Grenze, ist dabei umstritten (vgl. Papalexiou und Koutsoyiannis, 2006; Harris und Brunner, 2011; McClenathan, 2013). In der vorliegenden Arbeit wird, in Einklang mit den Richtlinien der WMO (2009), explizit der nach Salas u. a. (2014) theoretische PMP-Niederschlag verwendet. Die eingeführten Methoden sind jedoch so konzpiert, dass sie auch mit alternativen Abschätzungen des PMP-Niederschlages verwendet werden können.

Gemeinsam ist allen PMP-Abschätzmethoden, dass die Unsicherheit der resultierenden Abschätzung zum Einen relativ gross (Klemes, 1993; National Research Concil, 2000), und zum Anderen schwierig zu quantifizieren ist (Micovic u. a., 2015; Salas u. a., 2014). Auch eine Validierung einer Abschätzung des PMP-Niederschlages ist aufgrund fehlender Referenzereignisse kaum möglich. Trotz dieser methodischen Schwierigkeiten ist der PMP-Niederschlag ein in Wissenschaft und Praxis etabliertes Konzept zur Herleitung hydrometeorologischer worst-case-Szenarien.

Probable maximum flood PMF

Ein worst-case-Hochwasser ist, analog zur obigen Definition des PMP-Niederschlages, die im physikalischen Sinne theoretisch erreichbare Obergrenze eines Hochwassers. Dies entspricht dem sogenannten PMF-Hochwasser, dem wahrscheinlich maximal möglichen Hochwasser. Dieses ist von der WMO wie folgt definiert:

> “PMF is the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed.“ WMO (2009)

Basierend auf der Annahme, dass der PMP-Niederschlag zum PMF-Hochwasser führt, kann für die Abschätzung eines PMF-Hochwassers die Abflussreaktion eines Einzugsgebietes auf den entsprechenden PMP-Niederschlag modelliert werden. Welcher Modellierungsansatz dabei konkret verwendet werden soll, ist in den Richtlinien der WMO (2009) nicht näher beschrieben. Eine allgemeine, jedoch nicht näher erläuterte Aussage diesbezüglich lautet:

> “Given the extreme magnitude associated with PMP, it is often considered unnecessary to adopt complex models to describe the process for the estimation of the PMF.“ WMO (2009)

Diese relativ vage Formulierung bringt zum Ausdruck, dass vergleichende Studien zur Wahl des Modellierungsansatzes bislang fehlen. In Wissenschaft und Praxis werden denn auch eine Vielzahl von Modellen und Parametrisierungsmethoden zur Abschätzung des PMF-Hochwassers verwendet, deren Komplexität und Prozessnähe stark variieren.

1.2.3 Weitere Methoden

Eine weitere, in der Praxis noch immer gängige Methode zur Abschätzung eines extremen Hochwasserereignisses ist die Anwendung von Faustformeln (z.B. nach BFE, 2008). Hierbei wird ein statistisch hergeleiteter Wert, beispielsweise das hundertjährliche Hochwasser HQ_{100} oder die mittlere jährliche Hochwasserspitze mHQ, mit einem regionalisierten oder arbiträr definierten Skalierungsfaktor multipliziert. Sowohl theoretische Überlegungen als auch praktische Anwendungstests zeigen jedoch, dass ein solches Vorgehen keine zuverlässige Abschätzung extremer Hochwasser zulässt (Schumann, 2012).

1.3 Problemstellung und Zielsetzung

Die aktuell in Wissenschaft und Praxis verwendeten Methoden zur Abschätzung des PMF-Hochwassers sind grösstenteils nicht dem aktuellen Stand von Rechenleistung und Prozessverständnis angepasst. Dies gilt erstens für die räumlich-zeitlichen Strukturen der geschätzten Maximalniederschläge (PMP). Die Richtlinien der WMO (2009) entsprechen im Wesentlichen denjenigen aus dem Jahre 1986 (WMO, 1986) und beschreiben lediglich die Implementierung relativ einfacher räumlich-zeitlicher Niederschlagsverteilungen, wie zum Beispiel die Annahme eines gleichmässig verteilten Niederschlagsfeldes oder die Aufprägung einer elliptischen Form, und eines einfachen zeitlichen Verlaufes. Die aktuell verfügbare Rechenleistung ermöglicht jedoch die Berücksichtigung von komplexeren räumlich-zeitlichen Niederschlagsverteilungen, was möglicherweise zu einer höheren PMF-Schätzung führt.

Ein erstes Ziel der vorliegenden Arbeit ist daher die Entwicklung einer Methode zur hochwassermaximierenden räumlich-zeitlichen Verteilung des PMP-Niederschlages unter Berücksichtigung physikalisch determinierter Grenzen.

Weiter ermöglicht die Zunahme der verfügbaren Rechenleistung die Anwendung komplexerer Modelle zur Herleitung des PMF-Hochwassers aus dem PMP-Niederschlag. Die relativ neue Möglichkeit zur Kopplung von hydrologischen und hydraulischen Modellen erlaubt, verglichen mit der alleinigen Anwendung eines deterministischen hydrologischen Modelles, eine detailliertere Simulation des Fliessprozesses. Der Einfluss einer solchen Modellkopplung auf die PMF-Abschätzung wurde bislang noch nicht eingehend untersucht. Das Ziel für den zweiten Teil der vorliegenden Arbeit lautet demnach, den möglichen Mehrwert der Kopplung eines hydrologischen Modelles mit einem hydraulischen Modell, gegenüber der alleinigen Anwendung eines deterministischen hydrologischen Modelles, für eine PMF-Abschätzung zu beurteilen.

Die Wahl einer Methode zur räumlich-zeitlichen Verteilung des PMP-Niederschlages und die Wahl des Modellierungsansatzes, um aus einem PMP-Niederschlag ein PMF-Hochwasser zu simulieren, werden in den beiden obgenannten Zielen als unabhängig voneinander betrachtet. Der Einfluss der Wahl der Methode zur räumlich-zeitlichen Verteilung des PMP-Niederschlages kombiniert mit dem Einfluss der Wahl des Modelliersungsansatzes zur Abschätzung eines PMF-Hochwassers wurde bislang nicht systematisch untersucht. Ein drittes Ziel der Arbeit ist es daher, den kombinierten Einfluss zwischen räumlich-zeitlicher Verteilung des PMP-Niederschlages und der Wahl des Modellierungsansatzes auf eine PMF-Abschätzung zu beurteilen.

In der vorliegenden Arbeit bezieht sich der Begriff des PMF-Hochwassers explizit auf die Abflussspitze am Einzugsgebietsausfluss. Diese Präzisierung ist in zweierlei Hinsicht von Bedeutung:

- Das generierte Abflussvolumen kann in bestimmten Situationen eine wichtigere Zielgrösse darstellen als der Spitzenabfluss. Die relevante Zielgrösse ist von der Lage, der Topographie und der Grösse des Einzugsgebietes, sowie vom erweiterten Kontext und der spezifischen Fragestellung bestimmt. So ist zum Beispiel für die Dimensionierung einer Talsperre das Volumen des PMF-Hochwassers von grösserer Relevanz als der Wert für den dabei in den Stausee gelangenden Spitzenabfluss.

- Ein PMF-Hochwasser am Einzugsgebietsausfluss hat nicht zwingend zur Folge, dass jedes Gewässer innerhalb des Einzugsgebietes extreme Spitzenabflüsse aufweist. Das PMF-Hochwasser von Teileinzugsgebieten muss jeweils separat bestimmt werden.

1.4 Übergeordnetes Projekt und Einbettung der Arbeit

Mobiliar Lab

Die vorliegende Schrift wurde im Rahmen des Mobiliar Lab für Naturrisiken an der Universität Bern erarbeitet. Das Mobiliar Lab wurde im Jahr 2012 initiiert, um den Austausch und die Zusammenarbeit zwischen Wissenschaft und Praxis im Bereich der Erforschung von Naturgefahren zu verbessern. Die wissenschaftliche Seite wird dabei vom Geographischen Institut der Universität Bern repräsentiert. Als Praxis wird in erster Linie die versicherungswirtschaftliche Perspektive von Seiten der Mobiliar Versicherungen, aber auch diejenige von Anwendern im Planungs- und Ingenieurbereich, verstanden. Das Mobiliar Lab nimmt demnach eine Brückenfunktion zwischen Wissenschaft und Praxis ein.

Modellkette „M-AARE“

Das Teilprojekt „M-AARE“ im Rahmen des Mobiliar Lab hat zum Ziel, eine komplette Modellkette zur Simulation von atmosphärischen Prozessen bis hin zu daraus resultierenden Schadensereignissen zu entwickeln. Als Testgebiet dient dabei das Einzugsgebiet der Aare bis Bern. Die Modellkette und deren Komponenten sind in Abb. 1.1 dargestellt. Szenarien von Prozessen in der Atmosphäre werden dabei von einem globalen Klimamodell für einen Zeitraum von 600 (fiktiven) Jahren berechnet. Die in dieser Zeitreihe über dem Testgebiet vorkommenden Extremniederschläge werden in einem mehrstufigen Verfahren sowohl dynamisch, als auch statistisch auf das Testgebiet herunterskaliert. Die so erlangten Extremniederschlagsszenarien werden als nächstes in ein hydrologisches Modell gespiesen, um die darauf folgende Reaktion von verschiedenen Teileinzugsgebieten zu simulieren. Die daraus resultierenden Hochwasserganglinien der Teileinzugsgebiete bilden den Input für ein hydraulisches Modell, mit welchem der Fliessprozess im Gerinne simuliert wird. Auf diese Weise kann das Auftreten von Ausuferungen in der Modellierung berücksichtigt werden. Das Auftreten grossflächiger Überschwemmungen kann zudem verortet werden. Am Ende der Modellkette steht ein Schadensmodell, mit welchem die finanziellen Folgen für jeden simulierten Extremniederschlag abgeschätzt werden können. Mit der gesamten Modellkette kann schliesslich ein Zusammenhang zwischen Extremniederschlag induzierenden synoptischen Situationen und dazugehörigen Schadenpotentialen beschrieben werden.

Schadenabschätzung für ein PMF-Ereignis

In der vorliegenden Arbeit liegt der Fokus auf der Untersuchung von bestehenden Ansätzen zur Herleitung eines worst-case-Ereignisses sowie auf deren Weiterentwicklung. Die dabei erarbeiteten Modelle sowie die daraus gewonnenen Extremhochwasserabschätzungen dienen dabei zugleich als Teil der Modellkette des Projektes „M-AARE“. Der Aufbau der

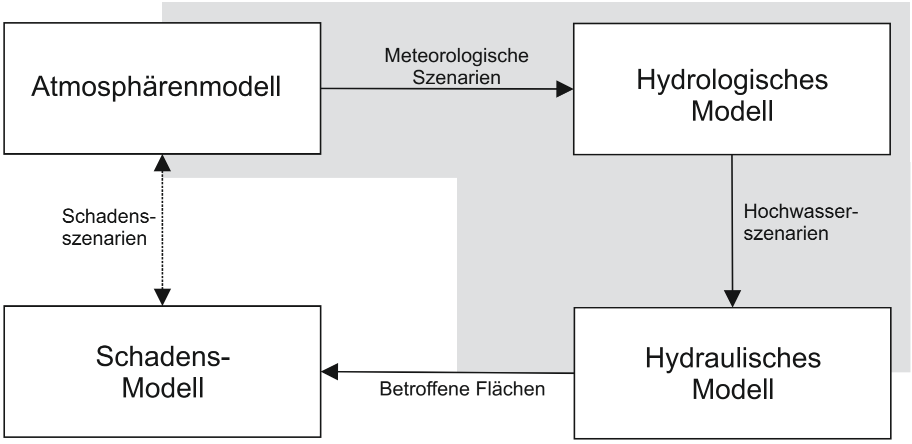

Abbildung 1.1: Schematische Darstellung der Modellkette „M-AARE“. Die vorliegende Dissertation dient als Beitrag zum Aufbau dieser Modellkette, mit Schwerpunkt auf den grau hinterlegten Teilen. In den beiden nur teilweise grau hinterlegten Teilen der Modellkette bilden die Arbeiten im Rahmen der vorliegenden Dissertation einen Teilbeitrag. Im Bereich der Modellierung atmosphärischer Szenarien sind das Szenarien für den PMP-Niederschlag, während weitere Szenarien für Niederschlagsereignisse bestimmter Jährlichkeiten nicht von dieser Arbeit abgedeckt werden. Im Bereich der hydraulischen Modellierung liefert die vorliegende Arbeit ein 1D-Modell des Untersuchungsgebietes, während im Rahmen des Projektes „M-AARE“ komplementär die Entwicklung und Anwendung eines 2D-Modelles angestrebt wird (vgl. Vetsch u. a., 2016).

Modellkette und die darauf folgende Modellierung von worst-case-Hochwasserszenarien soll schliesslich zu einer Abschätzung der PMF-induzierten Schäden beitragen.

1.5 Aufbau der Arbeit

Die vorliegende Arbeit besteht aus drei thematischen Schwerpunkten, welche in Abbildung 1.2 schematisch dargestellt sind. Im ersten Teil (Kapitel 2) wird der Systeminput behandelt, im zweiten Teil (Kapitel 3) die Modellierung des Systeminputs, und im dritten Teil (Kapitel 4) die Kombination von Systeminput und Modellierungsverfahren. Die wichtigsten Resultate aus den drei Teilen sowie ein kurzer Ausblick ist schliesslich zu einer Synthese zusammengefasst (Kapitel 5).

1.5.1 Teil 1: Niederschlagsverteilung

Die Herleitung eines PMP-Niederschlages als Systeminput kann in zwei Schritte unterteilt werden: Die Abschätzung des gesamten Ereignisniederschlages über einem bestimmten

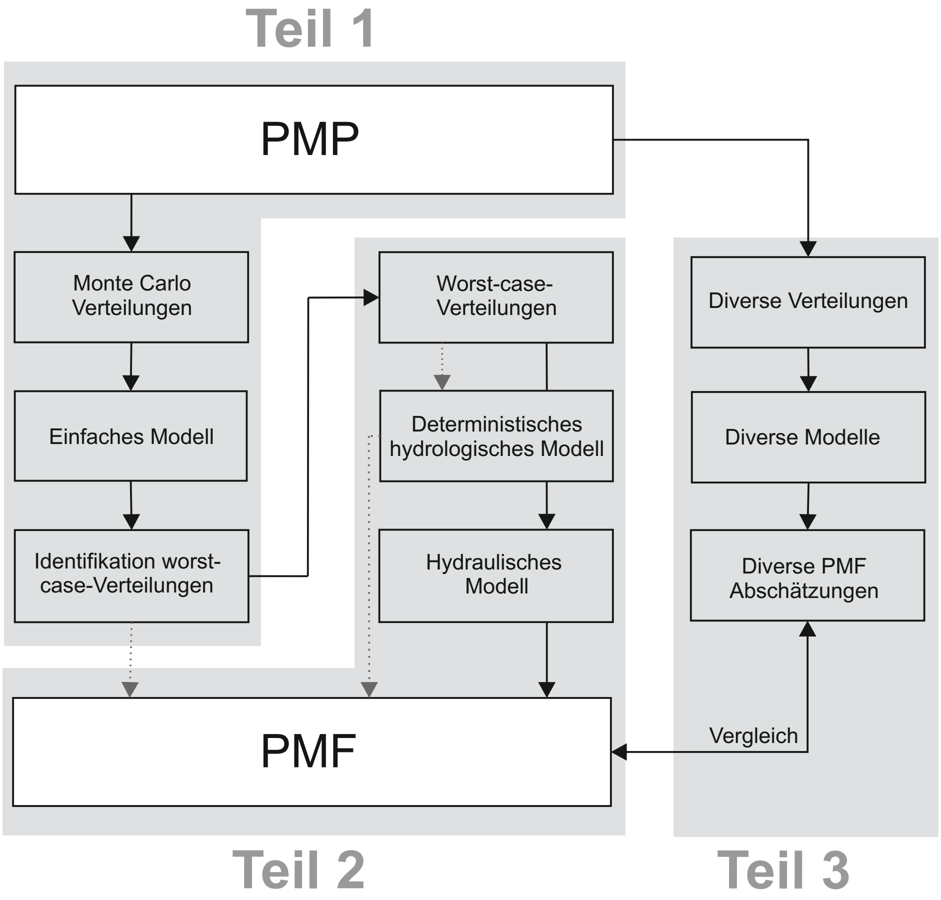

Abbildung 1.2: Aufbau der Arbeit. Der Ausdruck PMP steht für den vermuteten maximal möglichen Niederschlag (Probable Maximum Precipitation) und wird vorwiegend im ersten Teil der Arbeit behandelt. Der Ausdruck PMF steht für das vermutlich maximal mögliche Hochwasser (Probable Maximum Flood), dessen Modellierung im zweiten Teil der Arbeit betrachtet wird. Der dritte Teil der Arbeit beinhaltet eine systematische Betrachtung von verschiedenen Kombinationen von PMP-Niederschlagsverteilungen und Modellierungsansätzen.

Gebiet, und die räumlich-zeitliche Verteilung dieses Ereignisniederschlages. Die Vorgehensweise beim ersten Schritt, der Abschätzung des PMP-Niederschlages, wird meist nach den Richtlinien der WMO (2009) vorgenommen. Der berechnete Gesamtniederschlag wird anschliessend in einem zweiten Schritt räumlich und zeitlich so über dem Einzugsgebiet verteilt, dass die Einzugsgebietsreaktion maximiert wird. Die physikalische Plausibilität der Niederschlagsverteilung muss dabei stets gewährleistet sein. Die konkrete Verteilung dieses Niederschlages wird sowohl in der Wissenschaft als auch in der Praxis sehr unterschiedlich gehandhabt. In der vorliegenden Arbeit wird eine Methode eingeführt, in welcher der Gesamtniederschlag in einem Monte Carlo-Ansatz innerhalb der physikalischen Grenzen in möglichst vielfältiger Weise auf das Gebiet und über die Zeit verteilt wird. In einem vergleichsweise einfachen und effizienten hydrologischen Modell wird die Gebietsreaktion auf jede generierte Verteilung geprüft, um hochwassermaximierende Verteilungen zu identifizieren. Als Nebenprodukt dieses Ansatzes resultiert eine erste grobe Schätzung des PMF-Hochwassers.

1.5.2 Teil 2: Modellkopplung

Im zweiten Teil der vorliegenden Arbeit wird aus den in Teil 1 identifizierten worst-case-Verteilungen des PMP-Niederschlages das resultierende PMF-Hochwasser modelliert. Dabei kommen zwei unterschiedliche Modellierungsansätze zur Anwendung. Der erste Ansatz ist die Verwendung eines deterministisches hydrologisches Modelles, wie es zur Zeit in den meisten PMF-Abschätzungen verwendet wird. Der zweite Ansatz ist die Kopplung eines deterministischen hydrologischen Modells mit einem hydraulischen Modell. In letzterem wird die Reaktion von Teileinzugsgebieten modelliert, gefolgt von einer hydraulischen Modellierung der Prozesse im Gerinne und auf überflutungsgefährdeten Flächen.

1.5.3 Teil 3: Methodenvergleich

Im dritten Teil werden weitere Methoden der Niederschlagsverteilung sowie weitere Modellierungsansätze miteinander kombiniert. Dabei sind nur Methoden berücksichtigt, welche in den vergangenen Jahren für PMF-Studien angewandt wurden. Eine Ausnahme bildet dabei die im Rahmen des ersten Teils der vorliegenden Arbeit ausgearbeiteten Methode zur Niederschlagsverteilung, welche zum Vergleich herangezogen wird. Im Bereich der räumlich-zeitlichen Niederschlagsverteilung sind folgende Methoden berücksichtigt:

- Die Anwendung einer sowohl räumlich als auch zeitlich gleichmässigen Niederschlagsverteilung.
- Die Nachbildung von charakteristischen, elliptischen Sturmmustern.
- Die Anwendung der worst-case-Verteilungen aus Teil 1.

Aus dem auf drei Arten verteilten PMP-Niederschlag wird mit drei grundsätzlich verschiedenen Modellierungsansätzen das PMF-Hochwasser modelliert. Folgende Modellierungsansätze sind berücksichtigt:

- Ein Niederschlag-Abfluss-Modell basierend auf Einheitsganglinien und Einzellinearspeichern nach Maniak (2005).
- Ein deterministisches Niederschlag-Abfluss-Modell, wie es in den meisten PMF-Studien verwendet wird.

- Ein gekoppeltes hydrologisch-hydraulisches Modell.

Aus der Kombination der drei Methoden zur räumlich-zeitlichen Verteilung des PMP-Niederschlages und der drei berücksichtigten Modellierungsansätze resultieren schliesslich neun PMF-Abschätzungen. Darauf basierend wird schliesslich die Grössenordnung sowie die Plausibilität der PMF-Abschätzung aus der jeweiligen Methodenkombination beurteilt.

In einem Syntheseteil sind die Resultate aus den drei thematischen Teilen zusammengefasst, und die gewonnenen Erkenntnisse sowie die wichtigsten Schlussfolgerungen werden dargelegt. Weiter wird der Mehrwert methodischer Weiterentwicklungen beschrieben. Ein Ausblick gibt schliesslich einen Überblick über mögliche weiterführende Arbeiten. Zudem wird ein Ansatz zur Kombination statistischer und deterministischer Methoden diskutiert.

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2 An approach for the determination of precipitation input for worst-case flood modelling

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Hydrological Sciences Journal, accepted for publication.
`http://dx.doi.org/10.1080/02626667.2016.1151980`

Abstract

There is a lack of suitable methods for creating precipitation scenarios that can be used to realistically estimate peak discharges with very low probabilities. On the one hand, existing methods are methodically questionable when it comes to physical system boundaries. On the other hand, the spatio-temporal representativeness of precipitation patterns as system input is limited. In response, this paper proposes a method of deriving spatio-temporal precipitation patterns and presents a step towards making methodically correct estimations of infrequent floods by using a worst-case approach. A Monte Carlo approach allows for the generation of a wide range of different spatio-temporal distributions of an extreme precipitation event that can be tested with a rainfall-runoff model that generates a hydrograph for each of these distributions. Out of these numerous hydrographs and their corresponding peak discharges, the physically plausible spatio-temporal distributions that lead to the highest peak discharges are identified and can eventually be used for further investigations.

2.1 Introduction

Planning highly sensitive buildings and infrastructure (e.g. nuclear power plants, dams) often requires flood return level predictions that exceed the scope of today's methods. Indeed, extreme floods with return periods up to 10 000 years have to be estimated in some cases. Proper methodical procedures, however, are still missing; estimating such extreme flood peaks in a probabilistic, stochastic or combined way based on relatively short time series ($<$ 100 years) of discharge and precipitation data, or both, is not expedient. These approaches can be applied to estimate events with return periods only two to three times longer than the measured periods (Institute of Hydrology, 1999; Coles, 2004).

There are two different conceptual approaches that can be leveraged to estimate very low probability floods: A statistical approach based on observed data and a physical approach based on calculated maximum precipitation. The first approach relates peak discharges to return levels and is based on observed input data, which are used to feed rainfall-runoff models. However, with regard to predicting floods with very low probabilities, the methodical challenge of this approach lies in determining precipitation input, as scenarios with very low probabilities are required. To achieve a wider variety of precipitation events, the input dataset can be expanded in different ways. Several studies have produced a wide range of possible precipitation scenarios by resampling techniques (Brandsma and Buishand, 1998; Paquet et al., 2013), precipitation generators (Leander et al., 2005; Semenov, 2008; Furrer and Katz, 2008; Vandenberghe et al., 2010), statistical description of storm structures (Salvadori and Michele, 2006; Langousis et al., 2013) and bootstrap techniques (Uboldi et al., 2014). Such approaches can considerably improve the representation of spatio-temporal precipitation variability. However, they are still dependent upon manually predefined distribution functions and measured precipitation events. As can be concluded based on Verhoest et al. (2010), these methods aim mainly to reproduce rainfall time series in time and space. Moreover, Rogger et al. (2012b) show that the results of design flood estimations conducted in this way depend strongly on the applied method and furthermore on how the chosen method is applied. Even with specific modifications to the method (e.g. the use of information from historical floods), extreme value statistics does not allow for a reliable prediction of floods with return levels of 1000 years or more (Schumann, 2007; Merz and Blöschl, 2008; Schumann, 2012, e.g.).

As the methodical difficulties of predicting design floods with return levels of 1000 years or more are possibly insurmountable, it is appropriate to replace the prediction of events with very high return levels with a concept based on very unlikely events. This calls for the second approach, which examines the physical system boundaries in order to set an upper limit for a possible worst-case flood, but does not relate an estimation of a worst-case peak discharge with a probability and hence a return period. In this case, calculated probable maximum precipitation (PMP) amount is distributed over the catchment in space and time to feed a rainfall-runoff model and calculate a possible worst-case flood. The PMP is defined as "the theoretical maximum precipitation for a given duration under modern meteorological conditions" (WMO, 2009). The PMP is used to estimate a probable maximum flood (PMF), which is defined as "the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed" (WMO, 2009). Although this technique is widely used in daily practice, it is limited by two factors. Firstly, the concept of PMP implies the existence of a physical upper limit for areal precipitation, which does not necessarily exist (Koutsoyiannis, 1999; Papalexiou and Koutsoyiannis, 2006; Papalexiou et al., 2013). Secondly, the concept of PMP/PMF has been more or less "static", neglecting to sufficiently account for the decisive impact of temporal and spatial precipitation distribution on flood magnitude, i.e., only a few distributions have been considered so far.

Various approaches for the distribution of the PMP in space and time have been established, e.g. the station-average method, the Thiessen polygon method and the isohyetal method (McCuen, 2005; Beauchamp et al., 2013). These methods aim to distribute the PMP in accordance with spatial and temporal patterns of observed data. The disadvantage of these methods is that they lack the flexibility needed to produce a wide variety of distribution scenarios. Over the last two decades, the complexity of PMP distribution approaches has risen along with the increase in computation power. Approaches such as the stochastic storm transposition approach by Foufoula-Georgiou (1989) and Franchini et al. (1996) and the phase-state approach by Dodov and Foufoula-Georgiou (2005) have been established. These approaches aim to probabilistically reproduce patterns and parameters of observed storms. The main assumption underlying these approaches is that an appropriate storm regionalization is reasonable despite orographic and climatic influences. According to the authors, the approaches are able to produce realistic spatio-temporal precipitation distributions with very low occurrence probabilities. However, the produced storms and their parameters are still dependant on observed events and the estimation of the "tail-behaviour" of distribution functions, and therefore they may exclude improbable but physically possible distributions.

Thus, there is still a need for methods that adequately deduce precipitation scenarios with very low probabilities. The present study complements the physical system boundary approach for flood prediction with a new procedure to generate appropriate input data. The approach is based on the physical limits of precipitation and should contribute to a more reliable estimation of very unlikely events. In contrast to the existing precipitation distribution approaches which are either relatively inflexible (station-average, Thiessen-polygon, isohyetal distribution) or dependant on observations (stochastic storm transposition, phase-state), the proposed approach provides a method for generating a high number of spatio-temporal distributions of extreme precipitation and then identifying the potentially most hazardous distributions. The results can first be used to force sophisticated hydrological and hydraulic models, where the runoff processes during extreme events and specific side effects (e.g. landslides, inundations or log jams) can be taken into consideration for PMF estimation. Secondly they can be applied to rapidly estimate the likely distribution of peak discharges induced by a given amount of precipitation.

2.2 Methods

The basic concept of the proposed approach entails testing numerous spatio-temporal distributions of extreme precipitation in a given catchment. Any of the generated spatio-temporal distributions is used to iteratively force a simple model, as presented in the model design section. How these spatio-temporal distributions are generated is examined in the areal precipitation section. Finally, as explained in the model output section, the model generates one hydrograph for each generated spatio-temporal precipitation distribution. The spatio-temporal distributions leading to the highest peak discharges according to the model can then be used for further analyses.

2.2.1 Hydrological model

The transition from rainfall to runoff is calculated by a hydrological model. In this case, it is appropriate to choose a relatively simple model and to keep the computation time low. The model used in this study can be built for any desired mesoscale catchment, customized for the catchment-specific conditions. First, the catchment is divided into meteorological regions, taking into account the geographical and meteorological patterns within the basin. The meteorological regions will later be used to achieve a physically plausible precipitation distribution (as explained in Section 2.2). The relevant catchments within the meteorological regions are identified in order to depict distribution on a finer scale. The main criterion for this division is the availability of gauging stations. A schematic example of a possible model design is shown in Fig. 2.1. Runoff is modelled with a combination of unit hydrographs as proposed by Dooge (1959) and a simple routing for taking the flow durations between the catchments into account. Lakes inside a basin are handled as single linear storages; the outflow of the lakes can be estimated with rating curves describing the relationship between water level and discharge.

Plausible runoff coefficients are required to apply the described model. Based on former studies and considering the basin-specific characteristics, assumptions have to be made to estimate runoff coefficients in a practical way. In line with the aim of the proposed method, runoff coefficients have to be set in a way such that they represent a worst-case scenario.

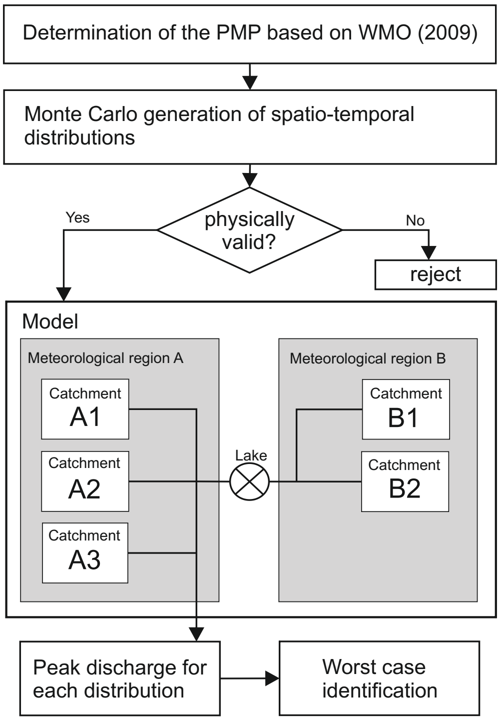

Figure 2.1: Sample scheme for a possible model set-up. The model is embedded in a Monte-Carlo framework to detect worst-case spatio-temporal precipitation distributions.

For most regions this entails extreme precipitation falling on an already saturated ground. This implies that a runoff coefficient on the upper boundary of observed events in the area of interest should be selected.

2.2.2 Areal precipitation

The areal precipitation input into a catchment has physically based limits, depending on geographical region under consideration. These limits can be approximated based on the assumption that the maximum supply of moisture is controlled by a region-specific threshold value for the absolute air humidity. This allows a maximum possible areal precipitation to be derived for a given region (WMO, 2009). Thus, areal precipitation for the total event duration based on WMO (2009) guidelines has to be deduced. This total amount of precipitation is then distributed over time and space, which is the main challenge of the approach seeking for the physical system boundaries. The PMP distribution is calculated in 5 steps.

1. First, a random temporal distribution of the total precipitation amount for the chosen duration has to be generated. To determine a random temporal distribution,

a proportion of the total event precipitation occurring at each time step is calculated. To avoid an implausible temporal distribution, the change of the ratio between the time steps t_x and t_{x+1} is limited to vary no more than 20%.

2. The meteorological regions are defined to consider the relatively independent behaviour of specific parts of the catchment, e.g. lowlands and mountainous regions, in terms of precipitation amounts and intensities. The total areal precipitation of time step tx is distributed by the Monte Carlo model over the meteorological regions. Then, the ratio between the precipitation in a meteorological region during time step tx and the total precipitation during time step t_x can be calculated. This difference in rainfall between time steps t_x and t_{x+1} must be not more than 20% to ensure that the generated precipitation distribution is spatially and temporally consistent.

3. The proportion of total areal precipitation of each time step and meteorological region is distributed randomly over the catchments within the respective meteorological region. The procedure outlined above leads to the random generation of a proportion of the respective total event precipitation for a catchment at any time step t_x.

4. Next, to confirm whether or not a generated distribution exceeds one of the given physical limits, the amount of precipitation of every time period and area is compared with the corresponding maximum possible areal precipitation based on WMO (2009). A distribution must be rejected if it exceeds at least one of the physical limits.

5. Finally, steps 1–4 are repeated to generate an arbitrary number of spatio-temporal precipitation distributions in a Monte Carlo process until an adequate number of physically valid distributions is available. A lower limit of $n = 10^4$ valid, i.e. physically plausible distributions is proposed. To reach this lower limit, approximately 10^6 iterations are necessary.

All random distributions are calculated by applying the Mersenne-Twister random algorithm by (Matsumoto and Nishimura, 1998). An example of a spatio-temporal precipitation distribution generated by following the procedures outlined thus far is shown in Fig. 2.2(a) (spatial) and Fig. 2.2(b) (temporal).

2.2.3 Model output and identification of worst-case distributions

The approach explained above generates a hydrograph for each spatio-temporal precipitation distribution. The resulting hydrographs represent the possible catchment reactions to the total precipitation input. The spatio-temporal distributions and their respecting hydrographs are useful in the following two ways:

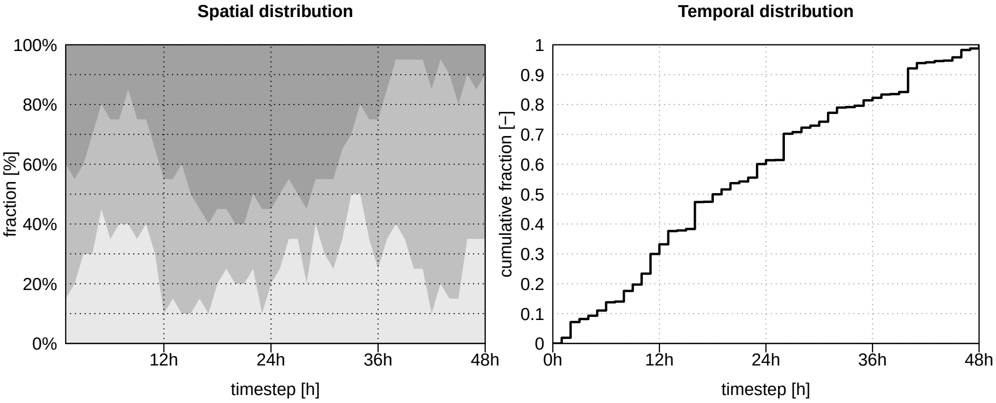

Figure 2.2: Left: Examples of randomly generated (a) spatial precipitation distribution, with each shade representing meteorological region, and (b) cumulative temporal precipitation distribution, for the entire catchment.

1. A wide range of precipitation distributions in space and time is considered, whereas the total precipitation input is held constant. This allows for the estimation of hydrographs with extreme peak discharges and therefore the estimation of the peak discharges that result from the assumed extreme precipitation events. The peak discharges of all the generated hydrographs from the maximum precipitation input can be converted into a distribution function of peak discharges under physically plausible precipitation conditions. As opposed to determining a single worst-case value, this takes into consideration the uncertainty of the spatio-temporal precipitation distribution of the maximum precipitation input.
2. It is assumed that spatio-temporal precipitation distributions that lead to high peak discharges in the model would also lead to high peak discharges in reality. Therefore, selected spatio-temporal precipitation distributions can be used for further worst-case studies, particularly as model input for sophisticated hydrological and hydraulic models.

2.3 Application

2.3.1 Study area

The approach is tested on the Aare-Bern basin, which covers an area of 2935 km^2 and is situated at the northern edge of the Swiss Alps. Its altitude ranges from 502 to 4272 m a.s.l. (average: 1610 m a.s.l.). About 8% of the basin area is glaciated, and there are two considerable lakes inside the basin. The highest peak discharges occur during summer, when the 0°C line is relatively high and when the floods are predominantly generated by heavy precipitation rather than by extreme snow and ice melt. The Aare River and its most important inflows have recently inundated their surrounding areas several times. Based on Fig. 2.3 it can be stated that there is a trend to higher peak runoffs during the last two decades. The four highest peak discharges, which exceeded the so far highest known observed peak discharge by 20-40%, took place during the last two decades. This leads to the question of where the upper limit of the hydrological system could possibly lie. The most severe observed events and their corresponding flood triggering effects, as well as other smaller scale events inside the basin, have been analysed in several studies (FOEN, 2000; FOEN, 2008; FOEN, 2009; Wehren, 2010; Rössler et al., 2014). Therefore, the state of knowledge about typical flood events and flood hydrology in this basin is relatively high. This ensures a good basis for the validation of new approaches. However, there is a gap of knowledge regarding extreme floods that reach the limits of the physical system.

2.3.2 Model design

The predictive model for the discharge of the Aare River in Bern was designed according to the scheme presented in Fig. 2.1 In this case, two meteorological regions are bounded by the outflows of the two largest lakes inside the alpine part of the basin, and the lower pre-alpine part of the basin represents the third meteorological region. To increase the spatial resolution of the model, each of the three meteorological regions was divided into four or five catchments. The location of the study area is shown in Fig. 2.4(a), and the associated three meteorological regions and 13 catchments are shown in Fig. 2.4(b).

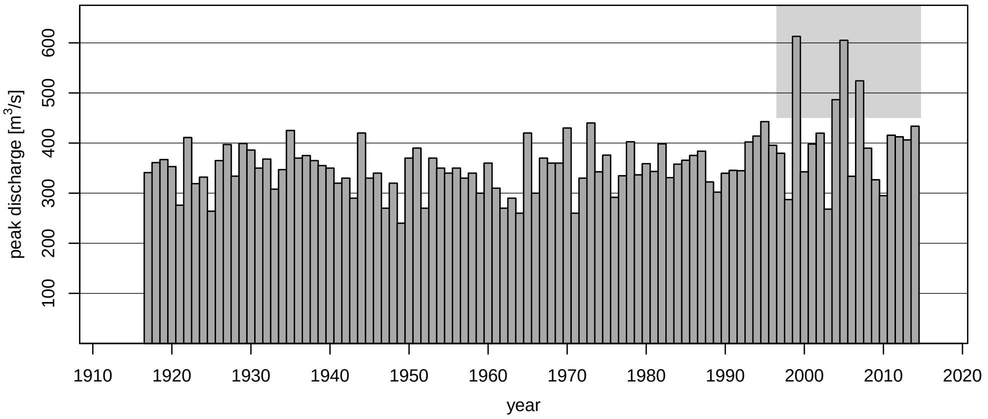

Figure 2.3: Observed annual maximum floods of the Aare River at Bern.

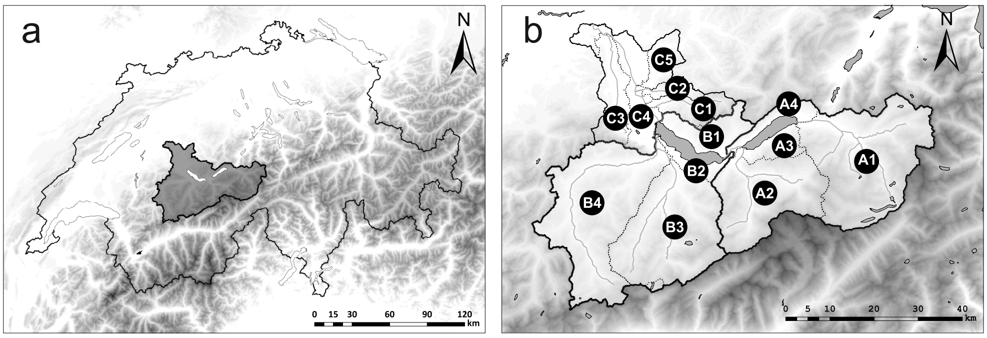

Figure 2.4: (a) The Aare basin at the northern edge of the Swiss Alps. (b) Division of the study area into three meteorological regions: A (East, 1145 km^2), B (West, 1265 km^2) and C (North, 525 km^2), with each meteorological region further divided into four or five catchments.

Precipitation

For Switzerland, which includes the study area at hand, Grebner and Roesch (1998) generated so-called area-quantity-duration (AQD) curves representing estimated physically plausible precipitation limits. Grebner and Roesch (1998) applied a method described in WMO (1986) which is similar to the indirect (watershed-) approach and to the local method described in WMO (2009). The curves were generated for various regions of Switzerland, and the curves for the region "West" were chosen for this case study. Grebner and Roesch (1998) have established AQD curves for the durations of 3, 12, 24 and 48 h and for areas from 1 to 5000 km^2. Unfortunately no curve exists for the 72-h duration. To incorporate this duration nevertheless, quotients of the highest measured 48- and 72-h areal precipitation amounts between 1961 and 2012 (MeteoSwiss, 2015) were calculated for each area size. Each point on the AQD curve for 48 h was multiplied with the corresponding calculated quotient to produce an AQD curve for 72 h. All mentioned AQD curves and curves for the highest measured values between 1961 and 2012 are shown in Fig. 2.5(a) and (b). Appropriate for the size of the considered catchment, the curves are given for an area of up to 3000 km^2. To assess whether the proposed method produces realistic precipitation distributions, the total amount of precipitation that was measured during the 2005 flood event (160 mm within 72 h) was redistributed by applying the procedure descripted above. Several of the 10 000 generated spatio-temporal distributions were close to the observed distribution in terms of the spatial as well as the temporal pattern. The comparison between the observed distribution and the best fit out of the 10 000 valid distributions is shown in Fig. 2.6.

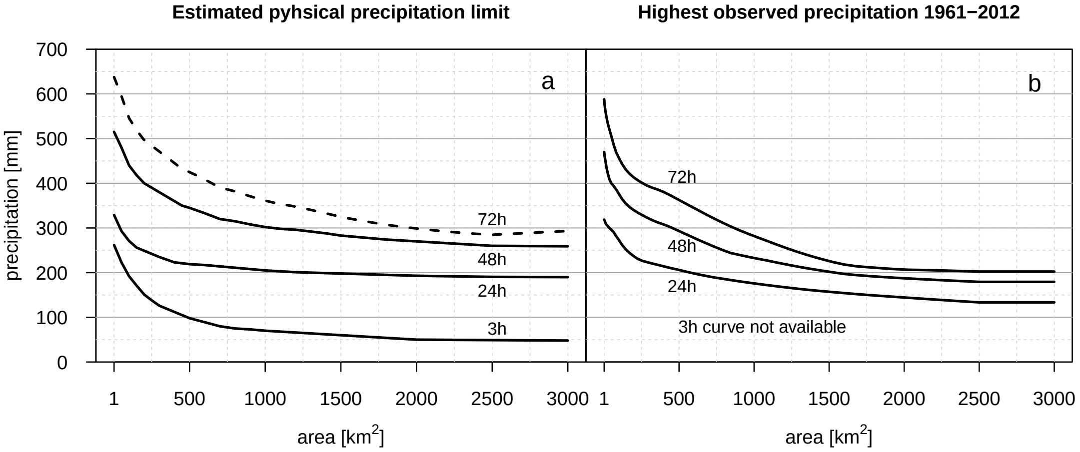

Figure 2.5: AQD curves generated by Grebner and Roesch (1998) for different event durations: (a) the dashed curve (72 h) was generated using the area-dependent quotient between the 48 h-curve and the 72 h-curve of the measured data. (b) Curves with the highest observed values in the case study area.

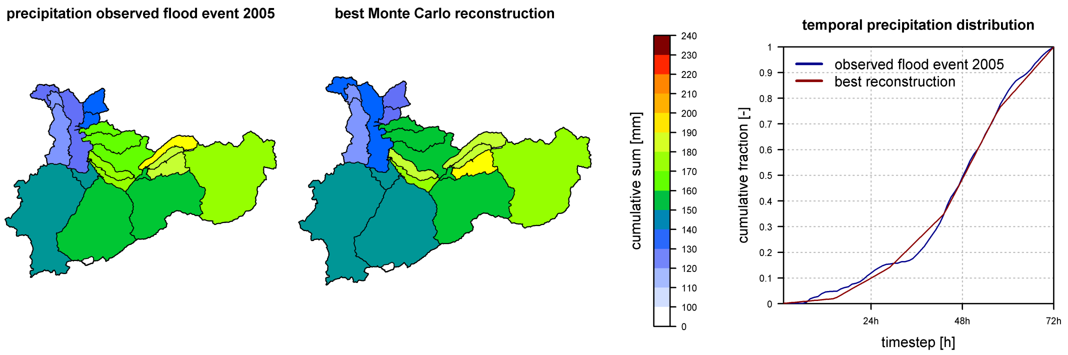

Figure 2.6: Observed spatial and temporal precipitation distributions of the 2005 flood event compared with the best reconstruction out of 10 000 valid generated distributions

Determination of the runoff coefficients

The highest observed runoff coefficients of catchments within the Aare Bern basin are close to 0.75 (Naef et al., 1986). According to Cerdan et al. (2004), the runoff coefficient generally decreases with an increasing catchment size. As all of the catchments analysed by Naef et al. (1986) represent portions of the Aare Bern basin, values above 0.75 are not expected for the entire basin. Because the source of this value is almost 30 years old (Naef et al., 1986), the annual peak flows from 1985 to 2012 of all gauged catchments were also checked using the available runoff series within the Aare basin. The results verified that the runoff coefficients were highly variable as expected, but none of them exceeded 0.75. Norbiato et al. (2009) came to the same conclusions for several catchments at the southern edge of the Alps. In addition, Merz et al. (2006) showed that runoff coefficients larger than 0.8 only apply when snowmelt processes are involved. However, the maximum precipitation depends on the moisture holding capacity of the air and thus on the air temperature. The precipitation thresholds calculated by Grebner and Roesch (1998) are associated with a relatively high temperature throughout the atmosphere, which is not expected to be possible during periods when snow is a crucial factor in runoff generation on basin scale. Therefore a runoff coefficient of 0.75 was chosen for the worst case.

Unit hydrographs

Following the procedure proposed by Dooge (1959), a unit hydrograph was calculated for each of the 13 catchments based on the highest ever measured event over the last 95 years, which took place in August 2005. Assuming the assigned precipitation in a catchment is uniformly distributed over space and time for each time step tx, the precipitation was first multiplied with the runoff coefficient and then added to the base flow, taking into account flow durations and the retention of the lakes. The calculation of the base flow is based on a two-parameter algorithm by Boughton (1986) in accordance with the suggestion by Chapman (1999). Daily precipitation data were gathered from the RhiresD dataset (MeteoSwiss, 2015) and disaggregated to hourly values using hourly data from stations located within the respective catchment. The discharge time series at the inflows of the two lakes and at the outflow of the catchment were obtained by the Federal Office for the Environment (FOEN). The model built according to the scheme in Fig. 2.1 is based on these 13 calculated unit hydrographs.

Lakes

The two lakes located inside the catchment, Lake Brienz and Lake Thun, have a buffering effect on the total runoff; hence, they must be incorporated in the model. The hydrological behaviour of the two lakes is represented by nonlinear relations describing the relationship between the water level and discharge data provided by the Department for Water and Waste of the Canton of Bern (AWA). Both lakes can be regulated to a certain extent by weirs; therefore regulation affects the relationship between water level and discharge. To best replicate the worst-case scenario in the study area, parameters were set to represent fully open weirs, reflecting the maximum possible outflow for every possible lake level. Anthropogenic flood mitigation measures like intentional lowering of the lake level before a forecasted extreme event are represented by applying the respective lake level.

Model performance

Data from the 2005 event (FOEN, 2008) were used to develop the unit hydrographs, so it can be seen as calibration event. The large flood events of 1987 (FOEN, 1991) and 2007 (FOEN, 2009) were used to validate to model. The runoff coefficients were adjusted according to the event-specific preconditions. This adjustment is reasonable as in this step only the shapes of the unit hydrographs are of importance, whereas the selected runoff coefficients in the model are not event specific but represent the worst-case. Figure 2.7 shows the observed hydrographs of the three events as well as the hydrographs simulated with the observed precipitation pattern. To validate the model sensitivity to spatio-temporal precipitation distributions, the total event precipitation was redistributed by applying the proposed Monte Carlo algorithm and then fed into the model. The resulting variation of time and magnitude of peak discharge shows that the model reacts sensitively to spatio-temporal precipitation variation.

For the calibrated 2005 event, the volume error is about 4%, where the discharge before the peak is overestimated and the discharge after the peak is underestimated. With regard to the two validation events, the volume error is about 5% for the 1987 event and about 4% for the 2007 event. Thus, the sum of the discharge is described with an adequate accuracy. The peak discharge, which is even more important for the purpose of this study, is estimated well; the deviation in each case is below 5%. The Nash-Sutcliffe Efficiency (NSE) criterion (Nash and Sutcliffe, 1970) for the 2005 calibration event is 0.88, and it is 0.61 and 0.88 for the 1987 and 2007 validation events, respectively. The relatively low NSE

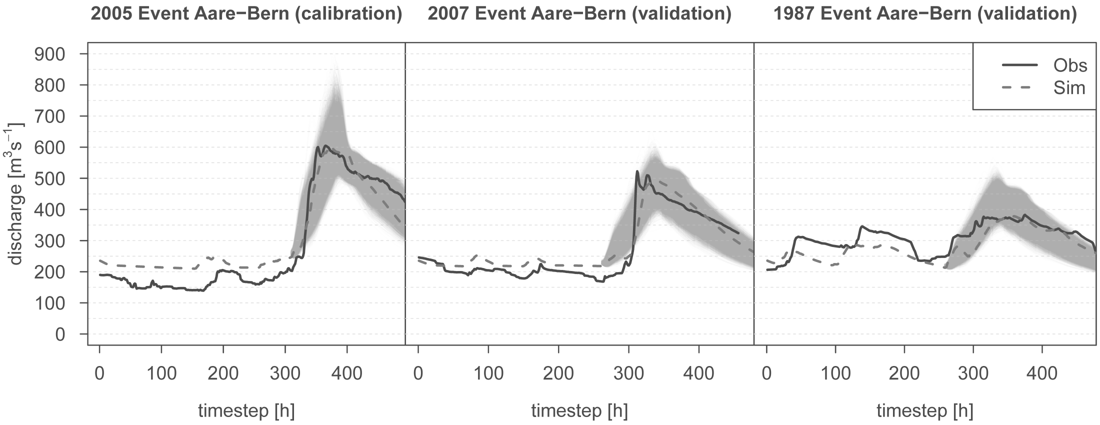

Figure 2.7: Measured and simulated hydrographs for the 2005, 2007 and 1987 events. The dashed line represents the model run with the observed precipitation data, the thin grey lines represent model runs with redistributed event precipitation and indicate the sensitivity of the model to the spatio-temporal precipitation distribution. The unit hydrographs were generated based on the 2005 event; hence it can be viewed as a calibration event.

for the 1987 event can be explained by the difference in process types between the 2005 calibration event and the 1987 event. The 2005 event, which was used to generate the unit hydrographs, was induced by 3 days of heavy rainfall on a saturated catchment (FOEN, 2008). In contrast, the 1987 event was the consequence of a relatively more persistent and less intensive continuous rainfall (FOEN, 1991). This can clearly be recognized by viewing the measured hydrographs in Fig. 2.7.

The 10^4 physically plausible precipitation distributions mentioned in Section 2.2.2 were elicited for event durations of 48 h and 72 h. A possible precipitation event lasting 47 or fewer hours is already included in the 48 h event duration in the form of a one sided temporal distribution (e.g. the possibility that the bulk of the total precipitation amount would fall within the initial hours).

2.4 Results

The result is the distribution of possible peak discharges induced by the maximum precipitation input and based on that the identification of critical spatio-temporal precipitation distributions. The hydrographs created with the 10^4 valid spatio-temporal distributions per event duration are shown in Fig. 2.8. The right boxplot in Fig. 2.9 shows the distribution of the corresponding peak discharges. For the applied spatio-temporal precipitation distribution over three meteorological regions and 13 catchments with event duration of 72 h, the median peak discharge amounts to 1140 m^3 s^{-1}, and the highest generated peak is 1575 m^3 s^{-1}. In the case of the 48 h event duration, the median peak discharge is 1160 m^3 s^{-1} and the highest generated peak is 1550 m^3 s^{-1} (not shown in the plot). The distribution of the peak discharges within this range depends on the spatio-temporal precipitation distribution.

The estimated values shown in Fig. 2.9 are plausible compared to former estimations, although they are clearly higher due to the maximization of the total event precipitation. An envelope curve of the highest observed floods was estimated by Weingartner (1999). However, recent flood events exceeded this envelope curve, which shows that this curve must not be considered an upper limit. The study by FOEN (2009), which was carried out for a 2000-km^2 catchment within the Aare Bern basin, is based on various precipitation scenarios. These scenarios were deduced from the highest observed flood event in 2005 by shifting and scaling the observed precipitation patterns. Considering that FOEN (2009) carried out their study on a smaller area of the catchment and applied a less maximizing approach based on observed events, the resulting model output is plausible. The spatio-temporal precipitation distributions which led to the peak discharges at the uppermost part of the resulting boxplot were identified as the most hazardous ones.

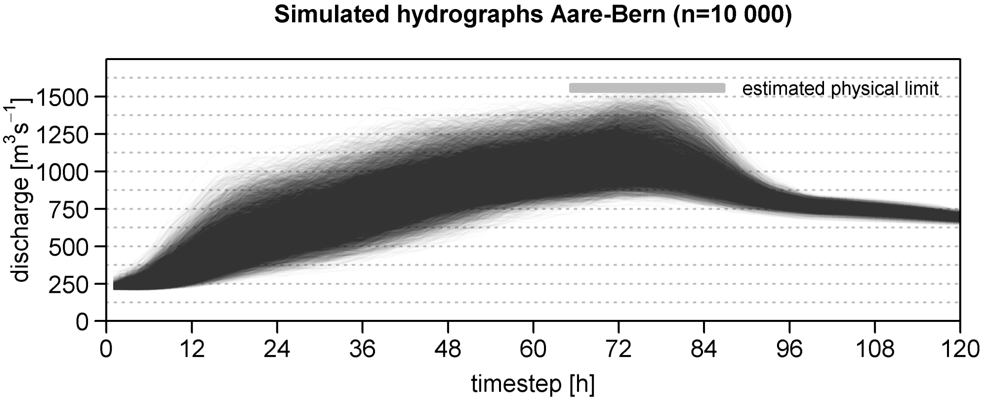

Figure 2.8: Example of the generated hydrographs for the event duration of 72 h. The single hydrographs represent the various spatio-temporal precipitation distributions as discussed in the Results section.

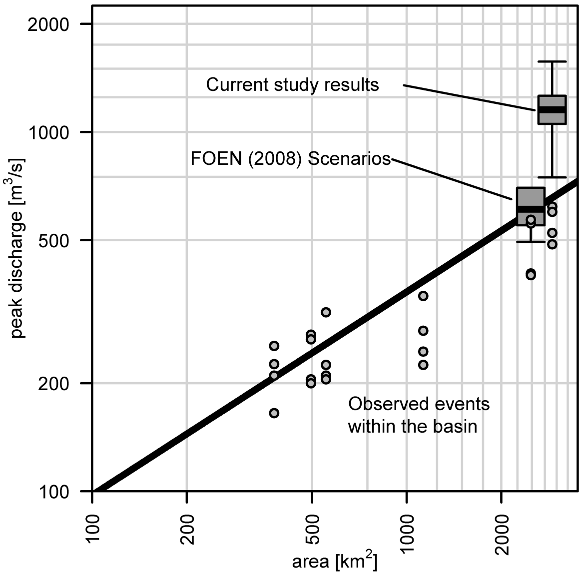

Figure 2.9: Range of peak discharges of each modelled hydrograph compared with the FOEN (2009) results and the envelope curve by Weingartner (1999). The points indicate the highest ever observed events of the Aare Bern basin as well as of smaller catchments within the basin. The boxplot to the far right represents the variation of catchment reactions to a given worst-case input due to varying spatio-temporal precipitation distributions.

2.4.1 Spatial and temporal sensitivity

Model outputs with relatively high and low precipitation fractions of each catchment were analysed separately to evaluate the model sensitivity to spatial precipitation distribution. These high and low precipitation fractions were identified as those falling in the 0.01 and 0.99 percentiles of the event precipitation per catchment. The resulting boxplots are shown in Fig. 2.10. The model sensitivity to the spatial precipitation distribution is mainly determined by the two lakes, which drain around 80% of the catchment area (meteorological regions A and B). In general, the model reacts more sensitively to the spatial precipitation distribution for the catchments that contribute directly to the runoff without traversing a lake (meteorological region C). The influence of catchments within a particular meteorological region is similar, whereas there is a relatively high variability of predicted peak discharge. To analyse the influence of temporal precipitation pattern on the model output, the events were divided into three categories based on temporal pattern and the according peak discharges were compared. Figure 2.11 shows that the applied model reacts sensitively to the temporal structure of the precipitation event. A higher peak discharge is modelled when the bulk of precipitation falls in the terminal phase of the event, which can be explained by the storage effect of the lakes. Overall, the influence of the temporal pattern on peak discharge is slightly smaller than the influence of the spatial pattern.

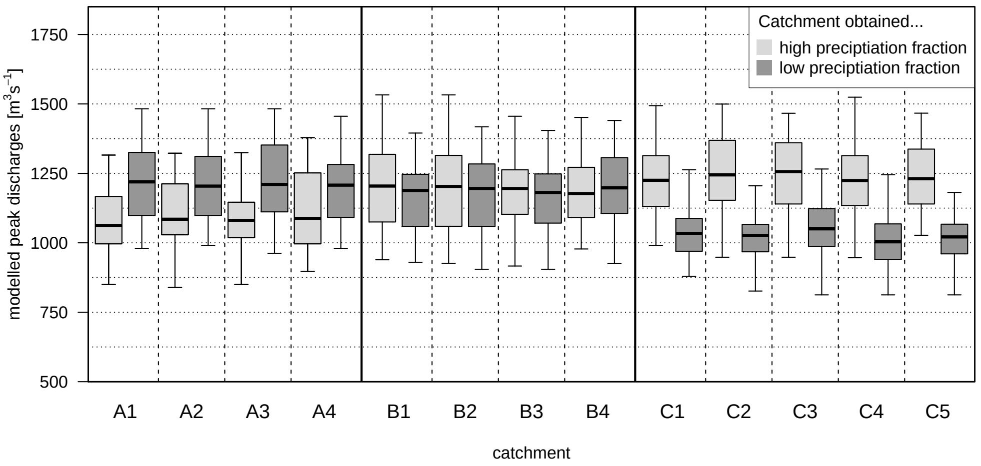

Figure 2.10: Range of the modelled peak discharges of model runs in which a particular catchment obtained an exremely high or low precipitation fraction. The peak discharge refers to the whole basin, e.g. the boxplot on the far left shows the distribution of the peak discharges of the whole basin resulting from all model runs in which the catchment A1 received a relatively high precipitation fraction.

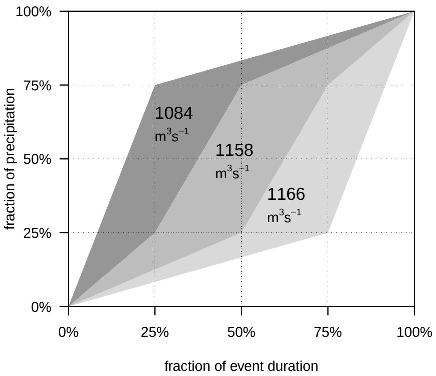

Figure 2.11: Median peak discharges from model runs in which the temporal precipitation distribution was congruent with the respective sector.

2.5 Discussion

The benefit of this approach is its relative simplicity, and therefore its relatively good practical applicability to various catchments. It allows for many different plausible spatio-temporal precipitation distributions to be generated and validated in a relatively short time. The validation of the model in the case study with the 1987 and 2007 events showed that the catchment reaction can plausibly be reproduced. Therefore, the method can be applied to carry out a first estimation of discharge values of a hydrological worst-case scenario. The generation of a wide range of possible spatio-temporal precipitation distributions for a given total event precipitation enables an estimation of possible worst-case floods without using manually predefined distribution functions. This is clearly a benefit compared to standard precipitation generators (Leander et al., 2005; Furrer and Katz, 2008; Semenov, 2008; Vandenberghe et al., 2010) or bootstrap techniques (Uboldi et al., 2014). Uncoupling the precipitation distribution from the parameters of observed events allows for the consideration of a great variety of possible patterns. This also applies for the representation of the variation in storm motions and storm velocities, which can also strongly influence subsequent PMF estimation (Seo et al., 2012; Nikolopoulos et al., 2014). Despite this uncoupling, some of the generated distributions are consistent with often observed patterns and correlations in space and time. Thus, the finally generated distribution of PMP is on one hand based on patterns similar to the ones observed, and on the other hand based on other physically plausible, but not yet observed patterns. In contrast, the stochastic storm transposition approach (Foufoula-Georgiou, 1989; Franchini et al., 1996; Dodov and Foufoula-Georgiou, 2005) primarily produces distributions that are similar to observed storm parameters and storm motions.

The main advantage of this method over resampling techniques (Paquet et al., 2013) and statistical description of storm structures (Salvadori and Michele, 2006; Langousis et al., 2013) is that the two steps of finding the worst-case flood causing precipitation distributions and implementing them in rainfall-runoff models are clearly separated. Therefore, the method ensures realistic conditions for the model input. Considering the fact that the applied hydrological model is not highly sophisticated due to the high number of required model runs, the result should be viewed as a rough estimation of the likely range of a PMF peak discharge. A subsequent application of sophisticated hydrological and hydraulic models allows for a more precise estimation in the consideration of step changes in runoff generation (Rogger et al., 2012a), variations in the initial conditions of the catchment, cryospheric influences on the runoff formation as well as catchment-specific event side effects like landslides, inundations and log jams. In this case, the highest peak discharge is considered to be the PMF.

Care must be taken in communicating the findings of studies applying this method. The exploration of physical precipitation limits and the usage of maximal precipitation based on WMO (2009) to force this model lead to results that are much higher than common estimations such as those for events with return periods of 100 years. The maximal precipitation input is a theoretical construct and events with the estimated precipitation intensities may never occur. One must consider that this method is based on several assumptions about the model input which are not ultimately confirmable. The maximum precipitation amounts are also calculated on the basis of several theoretical assumptions, and their level of uncertainty is unknown. To account for uncertainties that influence PMP estimation, Micovic et al. (2015) recently proposed to replace single PMP values with ranges of possible PMP values. In the present study, PMP estimations from neighbouring regions were tested to take into consideration that the PMP estimations could be slightly different. This resulted in a slightly lower median (-8%) and in a lower maximum (-12%). The proposed method is applicable to catchments that are between 1000 and 10 000 km^2. If the catchment size is less than 1000 km^2, flood triggering processes on a catchment scale are more decisive than spatio-temporal precipitation distribution (e.g. persistent convective thunderstorms). If the catchment size exceeds 10 000 km^2, the superposition of different processes, the occurrence of independent precipitation events and the interplay among different processes become more important. However, this would also increase the calculation time of each model run and therefore negatively affect the applicability of the model to a Monte Carlo approach.

2.6 Conclusions and perspecitves

By applying a simply built model, plausible spatio-temporal precipitation distributions that reveal high peak discharges can be generated by using a Monte Carlo approach. The scenarios generated by this method can be used as a foundation for more complex hydrological models than that used in this study. Besides identifying critical but realistic spatio-temporal precipitation distributions for further investigations, the method provides an estimation of the range of peak discharges that can be expected. Finding an appropriate method for estimating peak discharge iteratively approaching the physical limit of a basin is still a challenge; at least for estimating system precipitation input and its spatio-temporal distribution, the present approach constitutes a step towards methodical reliability and allows the estimation to be based on different, varying methods, as proposed by Gutknecht et al. (2006).

Acknowledgements

The authors would like to thank the Federal Office of Environment (FOEN), the Federal Office for Meteorology and Climatology (MeteoSwiss) and the Department for Water and Waste of the Canton of Bern (AWA) for providing the necessary input data. Anne de Chastonay, Fabia Hüsler, Ole Rössler and Bernhard Wehren are acknowledged for their thoughtful comments.

Funding

This study is funded by the University of Bern and the Mobiliar Lab for Natural Risks.

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3 The effect of a coupling of hydrologic and hydrodynamic models on PMF estimation

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Journal of Hydrology, 2016, http://dx.doi.org/10.1016/j.jhydrol.2017.04.052

Abstract

Deterministic rainfall-runoff modelling usually assumes a stationary hydrological system, as model parameters are calibrated with and therefore dependant on observed data. However, system behaviour is probably not stationary in the case of a PMF where discharge greatly exceeds observed flood peaks. Developing hydrodynamic models and using them to build coupled hydrologic-hydrodynamic models can potentially improve the plausibility of PMF estimations. This study aims to assess the potential benefits and constraints of coupled modelling compared to standard deterministic hydrologic modelling when it comes to PMF estimation. The two modelling approaches are applied using a set of 100 spatio-temporal PMP distribution scenarios. The resulting hydrographs, the resulting peak discharges as well as the reliability and the plausibility of the estimates are evaluated. The results show that coupling hydrologic and hydrodynamic models substantially improves the physical plausibility of PMF modelling, although both modelling approaches lead to PMF estimations for the catchment outlet that fall within a similar range. Using a coupled model is particularly suggested in cases where considerable flood-prone areas are situated within a catchment.

3.1 Introduction

Safety is a priority for communities when it comes to sensitive or potentially hazardous infrastructure like hydropower dams or nuclear power plants. In some cases, legal requirements define that such infrastructure has to be protected against any conceivable natural hazard that could occur. Therefore, governmental institutions as well as insurance companies are interested in a quantification of the possible worst-case scenario. Thus, various approaches for calculating the probable maximum flood (PMF) have been developed and applied in the course of the last several decades.

The World Meteorological Organization (WMO) defines the PMF as "the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed." It is derived by converting the PMP into runoff (WMO, 2009). The concept and the uncertainty of PMP estimation has been assessed in several recent studies (Micovic et al., 2015; Papalexiou et al., 2013; Salas et al., 2014). The PMP is usually converted to the PMF using deterministic hydrological models calibrated with observed data (Beauchamp et al., 2013; Kienzler et al., 2015; Zeimetz et al., 2015, e.g.). This method assumes the hydrological system to remain steady, meaning that the system behaviour during the calibration period or the calibration event is presumed to be the same as it is during a PMF event. However, this assumption is questionable, since many protection measures are dimensioned to protect against design floods with return levels of 100 or 300 years. As soon as a catchment-specific threshold is reached, the system may no longer be steady (Sivakumar, 2009). At or beyond this threshold, new emerging retention areas (Lammersen et al., 2002), new flow paths (Huang et al., 2007; Vorogushyn et al., 2012) and changing runoff processes (Rogger et al., 2012b; Rogger et al., 2012a) can strongly affect the hydrograph shape and the peak discharge, due for example to failing protection measures or overflowing lateral dams. The peak discharge of a PMF is expected to exceed such catchment specific thresholds, making these factors relevant for PMF calculation.

When calculating the PMF, the unsteadiness of the hydrological system can be accounted for by coupling hydrologic and hydrodynamic models. This technique is particularly promising when the expected peak discharge may considerably exceed the observed maximum discharge or the river discharge capacity. A hydrologic model is used to determine the conversion from rainfall to runoff for a number of sub-catchments. The resulting hydrographs are used as upper boundary conditions of a hydrodynamic model, which is able to calculate the runoff process with much more precision than a hydrologic model. This is due to the fact that in hydrodynamic modelling routing is calculated numerically rather than conceptually, e.g. using a sequence of single linear storages in the HBV model (Bergström, 1995). This allows for the consideration of the effects of retention areas, dykes, bridge piers and other physical obstacles. With computation power increasing over the past decade, coupled modelling approaches have been developed for flood estimation. Several case studies (Biancamaria et al., 2009; Bonnifait et al., 2009; Laganier et al., 2014; Lian et al., 2007, e.g.) show the applicability of coupled hydrologic-hydrodynamic models in reconstructing observed flood events. Numerous studies show that hydrodynamic models are particularly useful for considering retention effects (Dutta et al., 2013; Kim et al., 2012; Meire et al., 2010; Skublics et al., 2014). A case study by Castro-Bolinaga and Diplas (2014) confirms the applicability of a hydrodynamic model for modelling extreme floods.

Despite the potential of coupling hydrologic and hydrodynamic models to increase the physical plausibility of PMF estimation, there is no systematic assessment of the effects of model coupling on PMF estimation. The aim of the present study is therefore to evaluate whether coupling hydrologic and hydrodynamic models improves the plausibility of PMF estimation. This is done in three steps:

- The existence of catchment-specific thresholds for non-steady runoff processes is assessed by forcing a hydrodynamic model with a continuous series of synthetic design hydrographs. This process allows for the identification of catchment-specific thresholds for widespread inundations that lie beyond the design flood levels.
- The PMP is fed into a deterministic semi-distributed hydrologic model. This is the most common PMF estimation method (Beauchamp et al., 2013; Kienzler et al., 2015; Zeimetz et al., 2015, e.g.).
- The same PMP is fed into a deterministic semi-distributed hydrological model which is externally coupled to a hydrodynamic model.

The hydrographs generated with the coupled model are then compared to the hydrographs generated with the standard hydrologic model using the same precipitation input. In this way, the applicability of both modelling approaches in terms of PMF estimation can be compared. The results are interpreted through the identification of catchment-specific discharge thresholds for inundation and retention effects.

3.2 Study area

3.2.1 Physical characteristics

The study area is the Aare catchment at the northern edge of the Swiss Alps. It covers an area of about 3000 km^2 and its mean elevation is about 1600 m a.s.l. A map of the study area is shown in Fig. 3.1. The catchment can be roughly divided into an upper section and a lower section. The upper section of the catchment consists of a steep mountainous and partly glaciated landscape. The sub-catchments in this mountainous area drain directly into two connected lakes. The outflow of the lower lake crosses over into the lower part of the catchment, which is a relatively wide valley with extensive flood-prone areas.

The catchment is well-researched and its hydrology is relatively well-known as a result of numerous studies that have been completed in the area (Rössler et al., 2014; Wehren, 2010, e.g.). The highest observed peak discharges during the observation period 1918-2015 have been well documented and reconstructed by the Swiss Federal Office for the Environment (FOEN, 1991; FOEN, 2000; FOEN, 2008; FOEN, 2009).

3.2.2 Division into sub-catchments

For modelling purposes, the catchment can be divided into 13 sub-catchments, as shown in Fig. 3.2. Eight of them are situated in the upper part of the catchment and drain into one of the two lakes. The other five sub-catchments are situated in the lower part of the catchment and drain directly into the Aare River. Two additional areas within the catchment are constituted by the two major lakes themselves. The main flood-prone areas are located around the two lakes and in the lower part of the catchment along the main river.

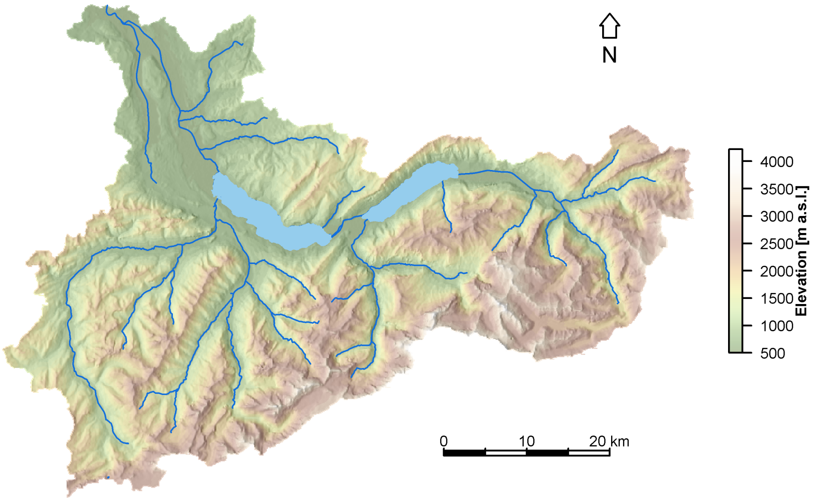

Figure 3.1: The Aare catchment situated at the northern edge of the Swiss Alps.

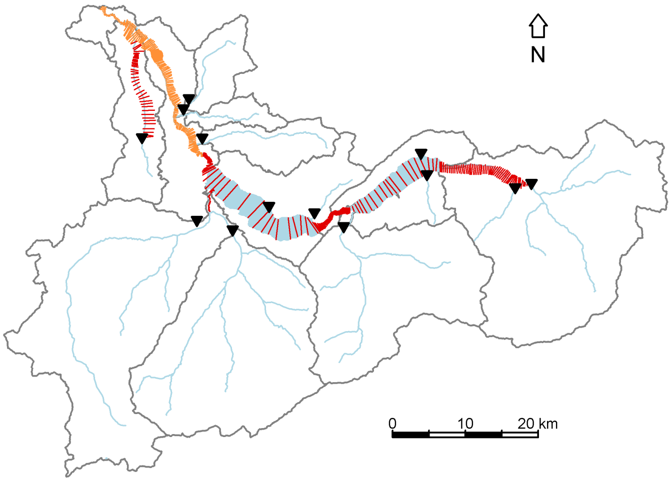

Figure 3.2: The division of the catchment into 13 sub-catchments and the range of the hydrodynamic model. The black triangles indicate the coupling points between the hydrological and the hydrodynamic model. The red lines indicate cross sections of the hydrodynamic model.

3.3 Methods

This study was carried out in four steps. First, synthetic design hydrographs were calculated and modelled hydrodynamically, allowing for the examination and identification of catchment-specific thresholds for widespread inundation. Next, PMP scenarios that could be used to force the two different modelling approaches were generated. Finally, the two modelling approaches were applied. The first approach entails the use of a deterministic hydrological model that was set up for the catchment. The second approach entails hydrological modelling of the sub-catchments within the catchment, where the hydrographs of the sub-catchments were used as upper boundary conditions for a subsequent hydrodynamic model. An overview of the river network, the coupling points between the hydrologic and hydrodynamic models and the spatial range of the hydrodynamic model is provided in Fig. 3.2.

3.3.1 Derivation and application of synthetic design hydrographs

Synthetic design hydrographs for the Aare catchment were derived using the guidelines proposed by Serinaldi and Grimaldi (2011). The synthetic unit hydrograph was calculated by fitting a two parametric gamma distribution as described by Nadarajah (2007) and Rai et al. (2009) to the structural hydrograph depicted by Serinaldi and Grimaldi (2011).

The procedure was applied to generate synthetic design hydrographs for a continuous series of peak discharges in intervals of 50 m^3s^{-1}. The synthetic design hydrographs were used as upper boundary conditions for the lower part of the hydrodynamic model (lower 30 km of total 80 km, orange cross sections in Fig. 3.2). The application of synthetic design hydrographs in the hydrodynamic model is based on the assumption that the full discharge volume flows through the lower part of the hydrodynamic model, which is not necessarily the case due to lateral inflows between the upper and lower boundaries of the hydrodynamic model. However, it is assumed that possible discharge thresholds for the occurrence of inundation and retention effects can reasonably be identified.

3.3.2 PMP estimation and spatio-temporal representation

The PMP for the event durations of 12 h, 24 h, 48 h, and 72 h were estimated following WMO guidelines (WMO, 2009). In order to identify the distributions that may cause the highest peak discharge at the study area outlet, the spatio-temporal distribution of the estimated PMP was deduced using a Monte-Carlo approach Felder and Weingartner (2016). Numerous randomly generated, physically plausible spatio-temporal distributions were tested by applying a hydrologic model where the random distribution was restricted to consider internal dependencies and correlations. In this case, approximately 10^6 PMP distributions were tested with the total precipitation amount held constant. The 100 physically plausible distributions that led to the highest peak discharges were considered most severe and are therefore applied in this study. The sample size of 100 spatio-temporal distributions is a compromise between the need for a large representative sample of distributions on the one hand and available computation power on the other. To ensure identical initial conditions for all model runs, the same observed meteorological environment was applied in modelling runs for each precipitation distribution. The meteorological environment represents medium summer conditions in terms of antecedent moisture. Summer conditions are used because the highest PMP estimation is based on summer atmospheric conditions.

This approach was chosen because it enables the derivation of a high number of slightly varying precipitation distributions. Applying a high number of varying PMP input scenarios allows for an assessment of the two different modelling approaches that is not dependent on how input data are chosen.

3.3.3 Hydrologic model PREVAH

The hydrologic modelling was done using PREVAH Viviroli et al. (2009a), which is a deterministic, semi-distributed, HRU-based hydrological model. The model has been extensively tested and applied in studies that deal with extreme hydrological events

(FOEN, 2009; Orth et al., 2015; Viviroli et al., 2009b; Zappa et al., 2015). These studies demonstrate the applicability of PREVAH to catchments like the Aare catchment. In the PREVAH model, the HRU's are directly routed to the catchment outlet. After modelling, additional routing can be applied by sequentially running several sub-models and incorporating intermediate lake modules. In this study, the sub-catchments (see Fig. 3.2) were independently modelled. Sub-catchments that drain into a lake were fed into the respective lake module. The sub-catchments situated between the lower lake and the catchment outflow were fed into an additional routing module.

The model has 12 parameters to be calibrated. The gauged sub-catchments were calibrated using the PEST calibration tool developed by Doherty (2004). The resulting NSE was between 0.70 and 0.92 for the calibration period (2001-2010) and between 0.65 and 0.88 for the validation period (2011-2014). The free parameters for the five ungauged contributing sub-catchments were estimated using the parameter regionalization approach developed by Viviroli et al. (2009b). Although it is not possible to evaluate this kind of parameter estimation specifically for ungauged catchments, Viviroli et al. (2009b) demonstrates that the parameter regionalization approach is appropriate. The hydrological model was not applied on the lakes within the catchment because they directly receive the precipitation that falls above them, and evaporation from the lakes was considered negligible.

3.3.4 Hydrodynamic model BASEMENT

The hydrodynamic model BASEMENT is a free hydrodynamic modelling system. The model is based on the continuity equation and solves the Saint-Venant equations for unsteady one-dimensional flow. A detailed derivation of the mathematical model applied in BASEMENT is illustrated in Vetsch et al. (2016).

In order to consider floodplains and storages outside the riverbed, the river cross sections were expanded to potential flood-prone areas. Cook and Merwade (2009) show that this procedure is advisable for modelling flood wave propagation, although the spatial details of the simulation of inundation depth and area are not as exact as in a 2D modelling environment. Cross sections of the riverbed and the directly adjacent levees were provided by the Swiss Federal Office of Environment FOEN. These cross sections were expanded to potential flood-prone areas beyond the levees using data from a digital elevation model with 0.5 m resolution and a vertical accuracy of 0.2 m. Considering the aim of this study, this resolution is sufficient for hydrodynamic modelling outside the riverbed because topographic details with major influence on flow paths and flow behaviour are sufficiently incorporated (Cook and Merwade, 2009; Mejia and Reed, 2011). The cross sections were set straight and perpendicular to the flow direction with average cross section spacing of approximately 150 m, as recommended in studies of other catchments (Ali et al., 2015; Castellarin et al., 2009; Samuels, 1990).

The hydrodynamic model was calibrated by empirically adjusting the Strickler coefficients (k_{str}). The values were adjusted by reconstructing the water surface elevation and the propagation time of the peak discharge of observed flood events. Particular attention was given to the peak discharge and the time to peak at different gauging stations along the river. The k_{str} values were set between 25 and 35 in the riverbed and between 30 and 45 in the floodplains outside the riverbed. Additionally, hydrodynamic parameters that define the characteristics of weirs (factor μ of the Poleni equation) and pipes (contraction factor) were adjusted. The hydrodynamic model was then able to reconstruct the rating curve at the catchment outlet with an error of ±2 cm in water level for observed flood events. In the range of a typical flood event, this corresponds to an error of approximately ±5 m^3s^{-1} or 1% of discharge, which is comparable to the error of the gauging station of about ±1 cm (FOEN, 1998). The error is assumed to be slightly higher in the PMF case during which areas would be affected that were not flooded during the calibration flood events.

3.3.5 Model coupling

The outputs of the hydrologic model are fed into the hydrodynamic model as upper boundary conditions or as lateral inflows. The model coupling is external, which means that there is no direct interaction between the models and backwater effects are only involved within the spatial range of the hydrodynamic model. The range of the hydrodynamic model was set to incorporate all significant flood-prone areas and potential retention areas. It is assumed that minor retention areas inside the sub-catchments have a negligible effect on the peak flow at the catchment outlet.

The coupling points between the hydrological and the hydrodynamic model are shown in Fig. 3.2. There are two cases where a coupling point lies significantly upstream of the sub-catchment outflow (see the most eastern and the most western coupling points in Fig. 3.2). In these cases, areas situated downstream of the coupling points were separately modelled and then added to the hydrodynamic model, following the suggestions of Lerat et al. (2012).

3.4 Results

3.4.1 Thresholds derived from the hydrodynamic modelling of synthetic design hydrographs

The calculated synthetic design hydrographs (see section 3.3.1) and the results of the hydrodynamic modelling of these synthetic design hydrographs are shown in Fig. 3.3.

The synthetic design hydrographs (on the left side of Fig. 3.3) that were used as upper boundary conditions are uniformly shaped. The hydrographs derived by hydrodynamic modelling (on the right side of Fig. 3.3) are identically shaped when peak discharges are below approximately 500 m^3s^{-1}. This corresponds to a peak discharge with a 30 year return period. Above that level, there are three clearly visible steps at approximately 570, 700 and 860 m^3s^{-1}. These thresholds indicate the occurrence of inundation and retention processes with significant influence on discharge processes. In consequence, the peak discharges of the synthetic design hydrographs on the model input side and the peak discharges of the calculated hydrographs on the model output side are no longer congruent. Two significant thresholds for emerging inundation and retention processes (700 and 860 m^3s^{-1}) are considerably above the 300 year return level flood; hence these thresholds do not affect floods below the 300 year return level but are possibly of crucial importance for PMF estimation.

3.4.2 Modelling the PMF

The hydrographs that were derived by hydrological modelling are shown in Figure 3.4. The hydrographs that were modelled by applying the coupled hydrological-hydrodynamic model are shown in Fig. 3.5. The hydrographs represent the modelled catchment response to the 100 PMP distributions described in section 3.3.2, where the precipitation event lasts from hour 0 to hour 72 or less depending on the temporal distribution of the PMP.

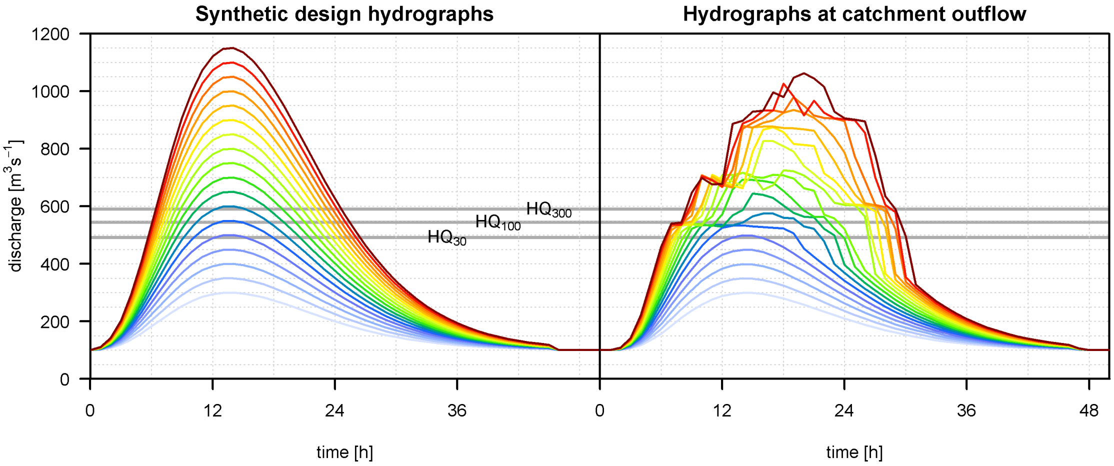

Figure 3.3: Synthetic design hydrographs that were used as upper boundary conditions of the hydrodynamic model and the resulting hydrographs at the catchment outlet. The grey lines indicate discharges with return periods of 30, 100, and 300 years.

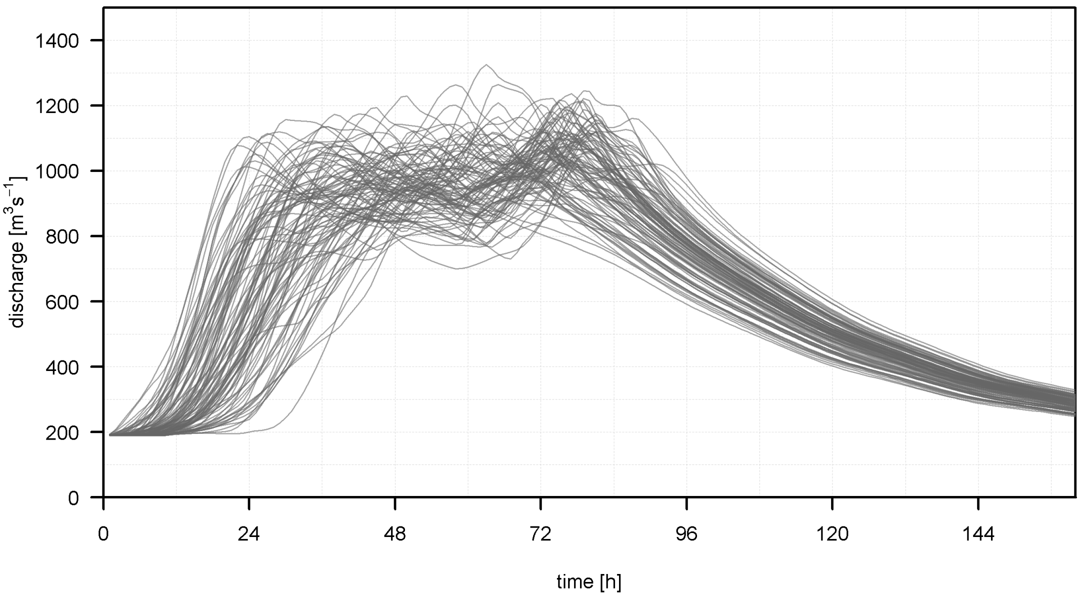

Figure 3.4: Hydrographs generated by the hydrologic modelling of the 100 PMP scenarios at the outlet of the catchment.

Hydrograph behaviour before peak discharge

The hydrographs resulting from hydrological modelling generally increase relatively quickly at the beginning of the event. In contrast, the hydrographs resulting from the coupled model generally rise more slowly. Comparing the shapes of the hydrographs from the two modelling approaches shows that the hydrographs derived by hydrologic modelling increase constantly and relatively smoothly. The hydrographs derived by the coupled model reflect distinct steps at certain discharge levels, e.g. at 700 m^3s^{-1}. This is due to the exceeded riverbed capacity and consequential inundations which delay further water level rise at the outlet. The hydrologic model is not able to capture this effect.

Peak discharge and PMF estimate

The peak discharges are between 1010 and 1320 m^3s^{-1} based on the hydrologic model and between 880 and 1220 m^3s^{-1} based on the coupled model. A comparison of the modelled peak discharges of all model runs is shown in Fig. 3.6. The plot shows that the coupled model generates lower peak discharges than the hydrologic model for most of the PMP distributions. However, there are also some scenarios where the coupled model generates a higher peak discharge than the hydrologic model. This is due to the retarding effect of lakes

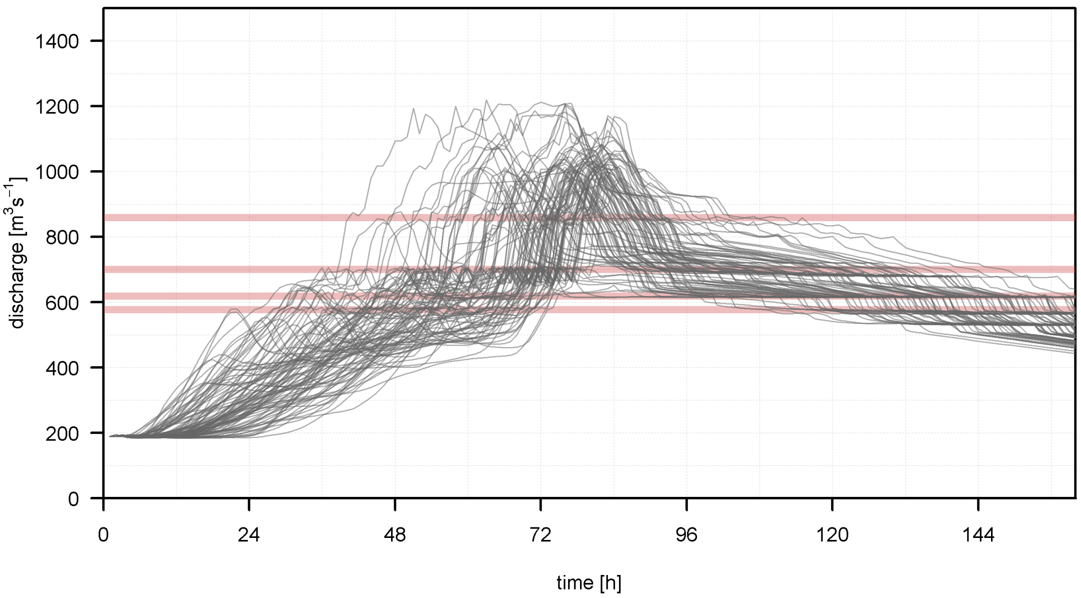

Figure 3.5: Hydrographs generated by the coupled hydrologic-hydrodynamic modelling of the 100 PMP scenarios at the outlet of the catchment. The red lines indicate thresholds for the occurrence of significant retention effects.

that are situated within the catchment. Precipitation distributions for which the coupled model generates the highest peak discharge are the ones that lead to a superposition of sub-catchment reactions. In such cases, in the first phase of the event the most intense precipitation occurs in the sub-catchments that drain into a lake. Subsequently, the lake water level rises. In the course of the event, the most intense precipitation shifts to the sub-catchments that are situated between a lake and the catchment outlet. This leads to the superposition of maximum lake outflow and maximum discharge from other sub-catchments. The hydrological model, with its relatively simple representation of the lakes, is not able to reproduce this effect in detail.

The time between the beginning of the precipitation event and the peak discharge (time to peak) of each model run is shown in Fig. 3.7. As demonstrated by the hydrographs in Fig. 3.4 and Fig. 3.5, there are considerable differences in time to peak between the two modelling approaches. The hydrological model generates peaks that occur from 25 to 87 h after the start of precipitation, while the coupled model generates peaks between 48 and 85 h after the start of precipitation. There is less temporal variation in the hydrographs generated by the coupled model than in those generated by the hydrological model. Considering that the total precipitation amount (PMP) was always held constant,

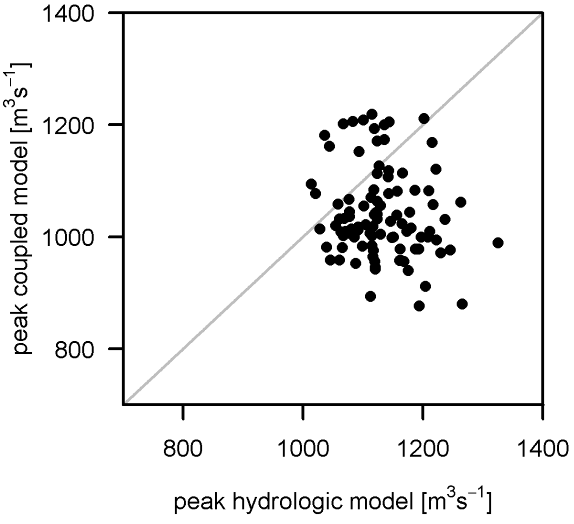

Figure 3.6: Peak discharges that result from the two modelling approaches.

Fig. 3.8 shows that the peak-to-volume ratios do not differ systematically.

Hydrograph behaviour after peak discharge

In both modelling approaches, the hydrographs drop considerably after the peak discharge is reached. In the coupled model, there are step changes visible again at various discharge

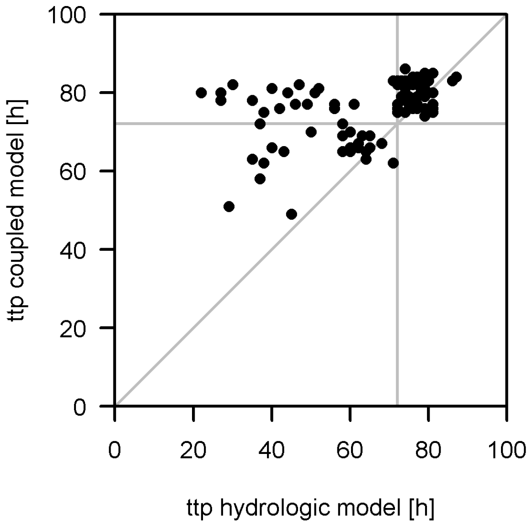

Figure 3.7: Time to peak that result from the two modelling approaches in hours. The vertical and the horizontal lines indicate the end of the precipitation event.

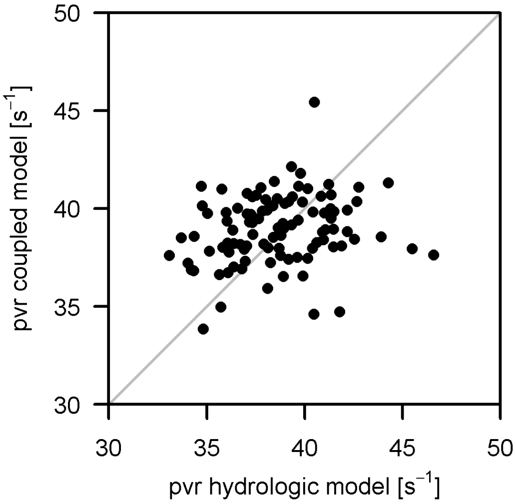

Figure 3.8: Peak-to-volume ratios that result from the two modelling approaches.

levels toward the end of the events (570, 620, 700, 860 m^3s^{-1}). These levels correspond to thresholds of the riverbed capacity at various cross sections thus the step changes can be explained by the flooding of floodplains. In a first phase, the discharge at the catchment outlet is reduced due to the amount of water that exceeds the riverbed capacity and inundates surrounding areas. In a second phase, the discharge at the same cross section falls below the discharge capacity of the river reach, and the inundating water masses flow back into the riverbed. In a last phase, when the surrounding areas are drained they do not contribute to discharge anymore, leading to a distinctive kink in the hydrograph.

3.5 Discussion

The hydrodynamic modelling of synthetic design hydrographs shows that retention effects are more pronounced when the estimated discharge considerably exceeds the maximum discharge of the calibration period. This is reasonable due to the fact that protection measures along the riverbed are often aligned to design floods of 30, 100 or 300 years, and not to floods with the magnitude of a PMF.

The hydrologic model and the coupled hydrologic-hydrodynamic model generate differently shaped hydrographs at the catchment outlet. The main difference in the two modelling approaches has to do with the representation of physical processes that occur within the catchment. The hydrological model represents the catchment reaction by using a set of calibrated parameters that usually define storage sizes, infiltration rates, evapotranspiration rates, and various other catchment characteristics. The calibrated model usually reproduces catchment behaviour that corresponds to catchment behaviour during the calibration period. However, the synthetic design hydrographs used in hydrodynamic modelling show that the catchment may deviate from its known behaviour due to the influence of effects that were absent during the calibration period. The deceleration of water flow due to changing riverbed characteristics, the storage and retention effects of inundated areas, as well as the depletion of lake storage capacity are possible reasons for such changing runoff characteristics. The hydrologic model does not consider non-stationary catchment behaviour or the superimposing effects that occur when discharge considerably exceeds the highest observed peak discharges of the calibration period, which presumably would occur in the case of a PMF event. Therefore it quickly routes heavy precipitation input to the catchment outlet. In contrast, the coupled model approach is less dependent on the occurrence of extreme events within the calibration period as it captures and reproduces the effects of high precipitation on the watershed. The representation of non-linear retention effects in the coupled approach allows for a more verifiable and a physically more reliable PMF estimation.

The differences between the hydrologic and the coupled model in terms of the representation of runoff processes have direct consequences for the shapes of the hydrographs and for the PMF estimation. The coupled model simulates peak discharges that are slightly lower than the ones generated with the hydrologic model. The time to peak is generally lower for the outputs generated by the hydrologic model than for those generated by the coupled model due to the relatively immediate routing of the runoff to the catchment outflow and the neglect of runoff-delaying processes like inundations in the hydrologic model.

An additional benefit of the coupled model approach is that it allows for the identification and mapping of affected areas and floodplains within the catchment. This allows for a better estimation of the possible consequences of a PMF event. The additional information on possibly affected areas is highly important for insurance and re-insurance purposes as well as for the planning of sensitive infrastructure or protection measures. However, various studies show that identification and mapping of affected areas are uncertain due to several critical factors, i.e. the model calibration (Pappenberger et al., 2005; Pappenberger et al., 2006; Remo et al., 2009; Di Baldassare et al., 2009), the lack of computation power limiting the consideration of various parameter sets (Altarejos-García et al., 2012), and uncertain design flood profiles (Brandimarte and Di Baldassarre, 2012). Chatterjee et al. (2008) show that 1D-2D model coupling improves the modelling of areal extent, water velocities, and the emptying process of retention areas in comparison to a 1D model, whereby it leads to comparable results in terms of peak discharge. However, such an approach requires significantly more computation power, a factor that limits the consideration of a high number of varying precipitation scenarios.

The setup and application of a coupled model is data-intensive and relatively time consuming. It usually requires pre-processing and calibration for every considered sub-catchment, the setup and calibration of a hydrodynamic model, and some effort for the coupling itself. Moreover, applying a coupled model involves a relatively long computation time. The availability of a high-resolution digital terrain model and river cross sections is required for coupled modelling. In contrast, the hydrological modelling approach only requires calibration of the sub-catchments, and the computation time is substantially lower than the computation time of a coupled model. Considering the similar range of peak discharges that were modelled by the two approaches, a hydrological model can reasonably be applied for rough PMF estimation in cases where only the catchment outlet is of interest or where the catchment is characterized by negligible potential retention areas. On the other hand, the coupled model better reflects physical reality when it comes to extreme floods. Using this approach is particularly imperative when retention areas in the catchment of interest may strongly influence PMF estimation.

3.6 Conclusion and Perspectives

In this study, PMF estimations were derived by applying a hydrologic model and a coupled hydrologic-hydrodynamic model in order to assess the advantages and constraints of these two modelling approaches. The two modelling approaches were tested with 100 PMP scenarios with the same volume of precipitation but different spatio-temporal precipitation distributions. The resulting hydrographs can be used to assess the applicability of the modelling approaches for estimating PMF at the catchment outlet and to evaluate the representation of physical processes within the catchment. The hydrological model is suitable to roughly estimate a PMF, particularly in cases where no significant retention areas are situated in the catchment. The application of a coupled hydrologic-hydrodynamic model is recommended for a better understanding of the physical processes within the catchment, for mapping purposes, or for the planning of flood prevention measures. A PMF event comprises substantially larger discharge volumes and substantially higher peak discharges than observed events. In the case of a PMF, flood protection measures that are dimensioned for specific return levels fail; thus widespread floodplain inundation and non-linear processes occur. This calls for the incorporation of a physical perspective to make estimation more reliable and comprehensible. The difference in the model outputs indicates the importance of studying the benefits and constraints of modelling approaches applied for PMF estimation.

Acknowledgements

This study is funded by the University of Bern and the Mobiliar Lab for Natural Risks. The authors would like to thank the Federal Office of Environment (FOEN), the Federal Office for Meteorology and Climatology (MeteoSwiss) and the Department for Water and Waste of the Canton of Bern (AWA) for providing the necessary input data. Anne de Chastonay is acknowledged for her thoughtful comments.

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4 Assessment of deterministic PMF modelling approaches

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Hydrological Sciences Journal, 2016, http://dx.doi.org/*10.1080/02626667.2017.1319065*

Abstract

PMF event estimation has challenged the scientific community for many years. Although the concept of the PMF is often applied, there is no consensus on the methods that should be applied to estimate it. In PMF estimation, the spatio-temporal representation of the PMP as well as the choice of modelling approach is often not theoretically founded. Moreover, it is not clear how these choices influence PMF estimation itself. In this study, combinations of three different spatio-temporal PMP representations and three different modelling approaches are applied to determine the PMF of a mesoscale basin keeping the antecedent catchment conditions and the total precipitation amount constant. The nine resulting PMF estimations are used to evaluate each combination of methods. The results show that basic methods allow for a rough estimation of the PMF. In cases where a physically plausible and reliable estimation is required, sophisticated PMP and PMF estimation approaches are recommended. The spatio-temporal representation of the PMP must always be in accordance with the applied modelling approach to avoid a distinct under- or overestimation of the PMF.

4.1 Introduction

Estimations of the probable maximum flood (PMF) are commonly required by planners dealing with sensitive infrastructure, such as nuclear power plants or hydropower dams, and are also of increasing importance to insurance and reinsurance providers. Engineers and catastrophe modellers regularly rely on PMF estimations, and their results are considered important parameters for worst-case assessments. The concept and the definition of the PMF are therefore widely used. However, various approaches with considerable methodological differences are used for its calculation.

The estimation of a PMF is based on the estimation of a site-specific probable maximum precipitation (PMP), which is generally calculated following World Meteorological Organization (WMO) guidelines (WMO, 1986; WMO, 2009). Then, the reaction of the catchment to the PMP input is deterministically modelled. The hydrograph or the peak discharge modelled in this procedure is considered to be the PMF. Although the concept of PMP/PMF has been critically discussed (Papalexiou and Koutsoyiannis, 2006; Papalexiou et al., 2013; Micovic et al., 2015), the fundamental procedure of deterministic PMF estimation is widely accepted. Though there is consensus on this general procedure, scholars disagree on how the single steps of this procedure should be carried out. Two main discordances will be further discussed.

The first substantial discordance is on how precipitation is represented in space and time. Several spatio-temporal representations of the PMP have been applied in recent studies. The simplest representation assumes a uniform precipitation distribution over space and time. Kienzler et al. (2015) in addition to various engineers and practitioners estimate PMF using this representation. Although a uniform distribution of the PMP over space and time is straightforward and easily applicable, Seo et al. (2012) show that the use of this approach generally "underestimates potential flood risk that could be exacerbated by rainstorm movement". Such rainstorm movement can be accounted for by applying the so-called isohyetal or hyetograph method, which is described by the National Weather Service (1982) and Cudworth (1989). In the isohyetal method, elliptical standard storm patterns (isohyets) are created in a way that the catchment reaction in maximized. The method is applied in recent PMF studies by Beauchamp et al. (2013) and Castro-Bolinaga and Diplas (2014). The hyetograph method leads to results that come closer to observed precipitation patterns. Regarding the PMF, however, this method can still lead to the exclusion of unlikely but physically possible precipitation distributions. These can be accounted for by using a Monte Carlo approach (Felder and Weingartner, 2016), which increases the number and the variability of considered spatio-temporal distributions. The Monte Carlo approach incorporates physically plausible distributions, although some generated patterns may deviate from observed distributions and are rather unlikely to occur. Salas et al. (2014) recently applied such a Monte Carlo approach. The compilation of several recent studies illustrates that fundamentally varying methods are used for generating spatio-temporal PMP representations. However, most of them do not provide theoretical justification for the methods they apply and there is no knowledge on how the choice of the precipitation pattern influences the PMF estimation.

The second substantial discordance on PMF estimation has to do with how the PMF is determined from the site-specific PMP, specifically which model type and model complexity is required to derive a reliable PMF estimation. According to the World Meteorological Organisation (WMO), "Given the extreme magnitude associated with PMP, it is often considered unnecessary to adopt complex models to describe the process for the estimation of the PMF" (WMO, 2009). However, this statement may rather be seen as a hypothesis than an assessment, as it ignores recent developments in modelling techniques and computation power that have allowed improved runoff routing and retention effect modelling. Recent PMF studies are based on various modelling approaches and model complexities. The most straightforward approach involves applying a transfer function that calculates runoff based on PMP, e.g. by using a Unit Hydrograph-based model, as applied by Cudworth (1989) and Felder and Weingartner (2016). Today, most of the PMF estimations in science and practice are calculated by applying a deterministic rainfall-runoff model (Beauchamp et al., 2013; Kienzler et al., 2015; Zeimetz et al., 2015; Yigzaw and Hossain, 2016). The most promising, but also the most intensive approach in terms of labour and computation power involves coupling a deterministic rainfall-runoff model with a hydrodynamic model. The application of such a coupled model potentially increases PMF estimation reliability because it incorporates retention and inundation processes. Castro-Bolinaga and Diplas (2014) successfully apply this approach. As is the case when it comes to spatio-temporal PMP representation, the choice of model type and complexity for PMF estimation is often not theoretically founded, and the influence of the selection of the modelling approach on the resulting estimation is unclear.

Several main factors have to be considered when it comes to selecting an appropriate methodological approach for PMF estimation:

1. The aim of a PMF study determines the required level of detail. For example, a simple approach may be sufficient for a preliminary study where only an approximation of the PMF magnitude is needed. In contrast, a PMF study that aims to determine potentially affected areas for insurance purposes requires high spatial resolution and high reliability. It therefore calls for applying a sophisticated model.

2. The researcher's expertise can affect the choice of a PMF estimation approach. Researchers may tend to choose approaches, and particularly models, with which they are familiar.

3. The availability of temporal, monetary and computational resources is often strictly limited. In consequence, this limits the applicability of certain methods and models.

4. The availability of geospatial, hydrological and meteorological data is a crucial factor

for the applicability of sophisticated methods and models. All data must be appropriate for the chosen PMF estimation approach and must fulfil its minimal requirements in terms of data quality, accessibility and temporal and spatial resolution.

5. The accessibility of information on concepts, methods and models is often limited. Emerging concepts, methods and models must be public and comprehensibly documented, which is not always the case.

This list is clearly not exhaustive, as there may be several more crucial factors that influence the choice of a PMF estimation approach. The choice of an appropriate PMF estimation approach, however, is basically a trade-off between these five aspects. The effects of these choices on the estimation itself are often neglected; it remains unclear how the application of different spatio-temporal PMP representations and modelling approaches influences PMF estimation. Gaining this understanding is of particular importance when it comes to relatively new and emerging modelling techniques, like the application of coupled hydrologic-hydrodynamic models.

The present study evaluates how various spatio-temporal PMP representations and modelling approaches influence PMF estimation. Depending on the purpose of a PMF estimation, highly sophisticated methods may not always be required. The aim of this study is therefore to assess whether or not the application of sophisticated PMF estimation approaches is always desirable. This assessment of various methods aims to inform the selection among spatio-temporal PMP representation approaches and PMF modelling techniques.

For this purpose, three different methods for representing PMP distribution over space and time are used to estimate PMF using three different modelling approaches. The catchment conditions as well as the total amount of event precipitation (cumulative PMP) are held constant. This results in nine independent PMF estimations that vary due only to the chosen spatio-temporal PMP representation and modelling approach.

4.2 Study area

The study area, shown in Fig. 4.1, is the Aare catchment south of Bern in central Switzerland. It is situated at the northern edge of the Swiss Alps and covers an area of about 3000 km^2. The catchment's mean elevation is 1600 m a.s.l., and it ranges from 4000 m a.s.l. at the alpine peaks in the most southern parts of the catchment down to 500 m a.s.l. at the catchment outflow in the most northern part of the catchment. The mean annual rainfall in the study area is about 1700 mm, of which approximately 400 mm are evaporated and 1300 mm are discharged. The highest observed peak discharge from the catchment is 620 m^3 s^{-1} (1918-2015), and the mean annual flood amounts to 360 m^3 s^{-1}.

The southern parts of the catchment consist of mountainous areas. Four major streams drain these mountainous areas into two lakes (see Fig. 4.1). The area that surrounds the lakes and the area downstream of the lower lake's outflow are relatively flat and contain widespread flood-prone areas. Due to the diversity of the landscape and the presence of lakes and widespread flood-prone areas in the study area is affected by numerous processes with various complexities, making it an ideal case for assessing the effect of model choice on PMF estimation.

Besides the physical characteristics of the catchment, the availability of knowledge and data support the choice of this study area. When it comes to meteorological and hydrological data, a relatively dense and well-established measuring network is available. The availability of highly resolved topographical data, namely a LIDAR-generated DTM with 0.5 m resolution, allows for processes that occur during flood events to be included in modelling. Data are provided by the Swiss Federal Office of Environment (FOEN), the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) and the Bernese State Office for Water and Waste (AWA). The hydrology of the catchment is well documented in former studies and flood-event analyses (e.g. FOEN, 2000; FOEN, 2008; FOEN, 2009; Wehren, 2010; Rössler et al., 2014).

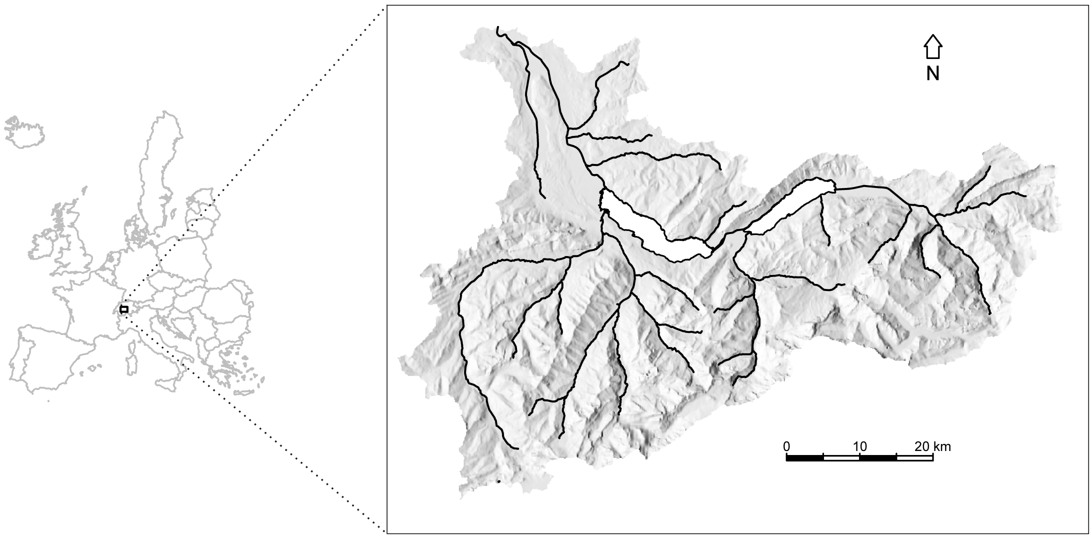


Figure 4.1: The Aare catchment located in central Europe. Four main torrents in the mountainous southern part of the catchment drain into the two lakes. Widespread flood-prone areas are situated downstream of the lower lake.

4.3 Methods

The main methodological differences among PMF estimations involve the use of different spatio-temporal PMP representation techniques and PMF modelling approaches. In this study, three different precipitation distribution approaches and three different modelling approaches are applied; nine varying combinations of precipitation distribution and modelling approach are considered. For each combination of methods, the calculated highest peak discharge represents the combination's PMF estimate. While other spatio-temporal PMP representation techniques and modelling approaches exist than the ones tested here, the techniques and approaches used in this study were selected because they represent fundamentally different techniques that are either frequently used in practice or emerging in science.

4.3.1 Spatio-temporal PMP distributions

This study relies on Grebner and Roesch's (1998) summer PMP estimation, which was calculated using WMO guidelines (WMO, 1986). The method applied by Grebner and Roesch (1998) corresponds to the indirect watershed approach described by WMO (2009). Based on Felder and Weingartner (2016), the estimated summer PMP depth used in this study amounts to approximately 300 mm for a 72 h event over 3000 km^2. This PMP amount is distributed over space and time, using three varying distribution approaches that have been applied in recent studies. An example of each of these spatio-temporal PMP distributions is shown in Fig. 4.2.

The simplest case of precipitation distribution is a uniform distribution over space and time. In this case, the estimated PMP of 300 mm was divided into 72 equal hourly amounts of 4.16 mm. These hourly amounts were then distributed uniformly over the catchment. Testing a uniform precipitation distribution makes it possible to assess the relative influence of the spatio-temporal precipitation distribution on PMF estimation in a comparative manner.

The second precipitation distribution approach considered in this study is the hyetograph method. This method is suggested by WMO (2009) and has been applied in various case studies Beauchamp et al. (e.g. 2013); Castro-Bolinaga and Diplas (2014). The hyetograph method aims to produce idealized storm patterns and storm motions based on observed storms. The orientation and movement of such an idealized storm can be varied in order to maximize the catchment reaction. The spatial pattern is usually elliptically shaped with a ratio of 2.5:1 between the two axes of the ellipse (National Weather Service, 1982). For the present study, a spatial pattern was generated that is roughly congruent with the considered catchment. The pattern was moved over the catchment in eight different directions. The pattern was slightly rotated in order to reproduce the motion of observed storms. The temporal distribution was set in a way that the bulk of the precipitation sum falls in the middle of the event. Orographic effects on the shape and on the motion of the idealized storm are neglected in this method.

The third precipitation distribution approach considered in this study is a Monte Carlo approach. In this method, the PMP is temporally distributed over single time steps and spatially distributed over a number of sub-catchments (Felder and Weingartner, 2016). The distribution is semi-random, meaning that inter-dependencies between single sub-catchments and a certain temporal dependency are considered. Compared to the hyetograph method, this approach is less dependent on patterns and motions of observed storms, but it still ensures physical plausibility by considering temporal and spatial dependencies within the catchment. In order to identify the distributions that maximize peak discharge, numerous precipitation patterns are iteratively fed into a hydrologic model. It is assumed that spatio-temporal precipitation distributions that maximize the peak discharge in a basic model are the most relevant for further investigation (Felder and Weingartner, 2016). For the present study, 10^4 physically valid precipitation distributions were modelled. The 100 distributions that led to the highest peak discharge were identified and considered for further PMF modelling.

The main differences among the applied precipitation distribution patterns are shown in Fig. 4.2. The uniformly distributed precipitation pattern does not show any variability

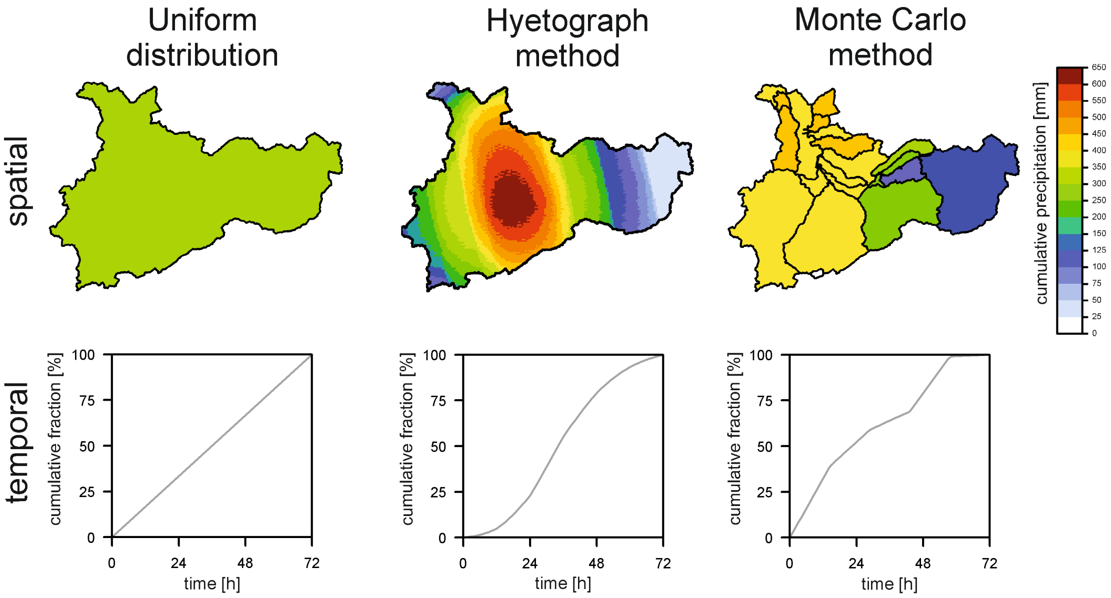


Figure 4.2: Examples of spatial and temporal patterns that result from the application of different PMP representation methods.

in time and space. The hyetograph method produces patterns that are elliptically shaped and have a certain temporal structure. The example shown in Fig. 4.2 is a storm moving from south to north that reaches the highest intensity above the central area of the catchment. The example of the Monte Carlo distribution shows a less smooth spatio-temporal distribution, and spatially the focus is more on a clear distinction between different meteorologically homogenous areas within the catchment than on a reconstruction of a storm motion.

4.3.2 Modelling approaches to determine PMF using PMP

This study considers three modelling approaches to evaluate the influence of model complexity on PMF estimation. A Unit Hydrograph-based model (in the following named UH-based model) was built in order to calculate the catchment reaction in a basic and straightforward way. For this purpose, Unit Hydrographs were calculated for three sub-catchments. Two sub-catchments cover the areas that drain into one of the two lakes indicated in Fig. 1; the third sub-catchment covers the rest of the area. The two lakes inside the catchment were handled as single linear storages. The runoff coefficient was set to 0.75, which corresponds to the upper limit of the reliable range according to the findings of Cerdan et al. (2004), Merz et al. (2006) and Norbiato et al. (2009). The model was calibrated using data from the highest observed flood event, which occurred in 2005, and validated for two relatively high observed flood events in 1999 and 2007. The resulting Nash-Sutcliffe criterion (NSE; Nash and Sutcliffe (1970)) is 0.88 (with a percent sum error of 4%) for the calibration event, and 0.61 (5%) and 0.88 (4%) for the two validation events.

The second modelling approach involves the use of a deterministic rainfall-runoff model. In this study, the hydrologic model PREVAH (hereafter referred to as the "hydrologic model") was set up for the study area. PREVAH is a semi-distributed conceptual hydrologic model that is based on hydrological response units (HRUs). It provides a routing module to take into consideration the flow durations within a catchment, and a lake module to account for lake storage effects inside the catchment. A detailed model description is provided in Viviroli et al. (2009). The model was parameterized using discharge time series from 2000 to 2010 (calibration) and 2011-2014 (validation). The resulting NSE is 0.92 for the calibration period and 0.81 for the validation period.

The most sophisticated modelling approach entails a coupled hydrologic-hydrodynamic model (hereafter referred to as the "‘coupled model"’). In order to apply it, the catchment was divided into several sub-catchments that drain into the main river. The reaction of the sub-catchments on the precipitation input was modelled using the hydrologic model PREVAH. The model was parameterized for each sub-catchment using a discharge time series from 2000 to 2010 (calibration) and 2011-2014 (validation). The main river and its surrounding flood-prone areas were modelled using the hydrodynamic model BASEMENT-ETH 1D (Vetsch et al., 2016). To incorporate retention and inundation processes that may occur outside the riverbed, the cross-sections were expanded to the flood-prone areas perpendicular to the flow direction. This relied on riverbed cross-section data acquired with a differential GPS system. The Swiss Federal Office for Environment provided these data. The cross-section information for flood-prone areas outside the riverbed was extracted from a DTM provided by the Canton of Bern. Its spatial resolution is 0.5 m with a vertical accuracy of ±0.2 m. The hydrodynamic model parameters (Strickler values, factor μ of the Poleni equation and contraction factors of pipes) were empirically derived by reconstructing observed flood events, with special focus on peak discharge and on flow duration along the main river.

The initial conditions in all three models were set in a way to represent average summer conditions in terms of antecedent soil moisture and initial storage levels. This ensured that the three modelling approaches were not influenced by varying initial conditions. For this study, the choice of average summer soil moisture conditions is reasonable because it corresponds with the season of the estimated PMP and because it is expected that differing model behaviour can be better identified under such conditions than under the assumption of fully saturated antecedent conditions.

4.3.3 Evaluation

As it is by definition not possible to validate a PMF estimation, evaluation is based on an assessment of the physical plausibility and reliability of an estimation and on an inter-comparison of the nine resulting estimations. For the evaluation, the result of the most sophisticated spatio-temporal representation of the PMP (the Monte Carlo method) applied with the most sophisticated modelling approach (the coupled hydrologic-hydrodynamic model) is considered to be the reference estimation. The reference estimation is used as a benchmark for the assessment of the eight other combinations. The underlying assumption is that this combination of PMP and modelling approach leads to the best estimation.

4.4 Results

The modelled hydrographs of all combinations of precipitation distribution methods and modelling approaches are shown in Fig. 4.3. The different methods of spatio-temporal PMP representation are shown in the rows. The different modelling approaches are shown in the columns.

The modelled hydrographs are highly varied in terms of magnitude of peak discharge, rising time and retention flow. The most straightforward option, namely the UH-based

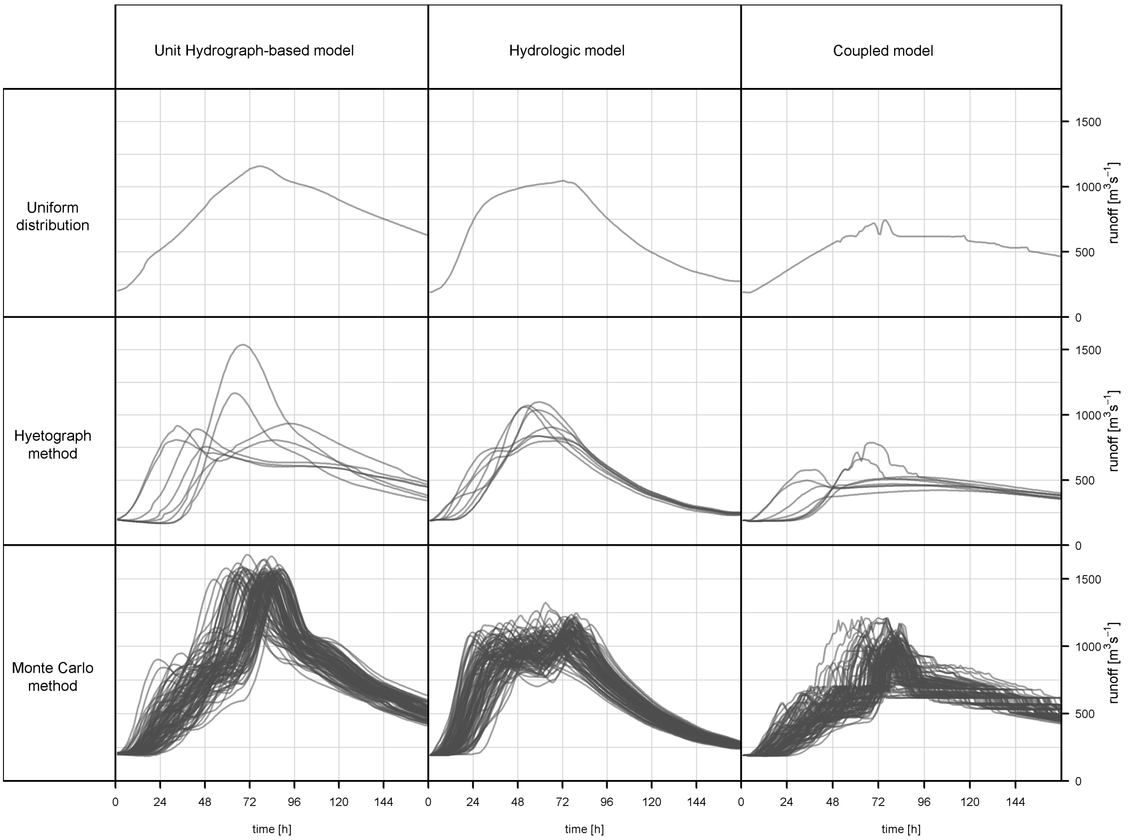


Figure 4.3: Resulting hydrographs of all combinations of the three spatio-temporal PMP representation approaches and the three applied modelling approaches at the outlet of the study area. The highest peak discharge of each combination is considered to be the corresponding PMF estimate.

model fed with a uniformly distributed precipitation input, results in a peak discharge of 1160 m^3 s^{-1}. The hydrograph shows a relatively constant increase before peak discharge and a slightly slower decrease after peak discharge. The shape of the hydrograph directly reflects the model setup, i.e. the constitution and the arrangement of the Unit Hydrographs and the representation of the lakes. The UH-based model fed with hyetograph precipitation patterns results in strongly varying hydrographs. In this case, the magnitude of the peak discharge depends mainly on the storm direction. The highest peak discharge calculated using this method amounts to 1540 m^3 s^{-1} and occurs when the generated storm moves in the direction of the catchment outlet from a region far away from the catchment outlet. In this particular catchment, this movement is from south-east to north-west. The precipitation patterns generated with the Monte Carlo approach fed into the UH-based model lead to the highest peak discharge of approximately 1680 m^3 s^{-1}. The UH-based model generally reacts linearly to incoming precipitation, with the exception of the effect of the two lakes.

The hydrologic model's reaction to a uniformly distributed PMP input is similar to the UH-based model's reaction, although when the hydrologic model is used the catchment reacts faster to heavy rainfall than when the UH-based model is used. This is mainly due to fact that the hydrologic model is able to differentiate between various precipitation intensities, meaning that extreme precipitation intensity leads to a relatively higher amount of direct runoff than a moderate one. Therefore, extreme precipitation, as applied in this study, reduces the modelled time to peak. In addition, the incorporation of various storages, e.g. soil moisture and groundwater storage, do affect the modelled catchment reaction when a hydrologic model is used. This effect lowers the modelled PMF by approximately 100 m^3 s^{-1} to 1050 m^3 s^{-1} compared to the PMF calculated with the UH-based model using the same precipitation distribution. Modelling the hyetograph distribution with the hydrologic model leads to similarly shaped hydrographs with the highest peak discharge at 1100 m^3 s^{-1}. The spatial structure of the precipitation pattern, an example of which is shown in Fig. 4.2, has a relatively small influence on the modelled catchment outflow. Regarding the hydrographs generated by the hydrologic model using the Monte Carlo-distributed precipitation, the modelled peak discharge is 1330 m^3 s^{-1}. As was the case using the UH-based model, the Monte Carlo precipitation distribution generated the highest peak discharge.

The application of a coupled model fed with the uniformly distributed precipitation leads to the lowest peak discharge of 750 m^3 s^{-1}, which is relatively close to the highest observed discharge of 613 m^3 s^{-1}. Remarkable are the distinct kinks in the hydrograph before and after peak discharge is reached. These reflect inundation and retention processes that are only considered in the coupled model. Using the coupled model, the precipitation distribution generated with the hyetograph method leads to a similar peak discharge of 790 m^3 s^{-1}. The modelled peak discharge is dependent on the design storm's direction of motion. Again, clear thresholds are visible, indicating the occurrence of inundation and retention processes. The application of the Monte Carlo-distributed precipitation patterns in the coupled model leads to a peak discharge of 1220 m^3 s^{-1}. The mentioned thresholds for inundation, retention and the emptying of retention areas (backflow into the river bed) are visible in all of the hydrographs. The Monte Carlo precipitation distribution leads to the highest peak discharge for this modelling approach as well.

The hydrographs that determine the PMF estimates, i.e. the hydrographs with the highest peak discharges, organized by applied modelling approach are shown in Fig. 4.4. Compared to the reference estimation (Monte Carlo precipitation distrubution fed into a coupled model), the UH-based model tends to overestimate the PMF. The hydrologic model shows less variation in the modelled peak discharges, and the peak discharges are relatively close to the reference peak discharge. In comparison to the reference estimation, the relatively short rising time and the smooth retention flows suggest that the behaviour of retentive storages is not well captured by the hydrologic model. The coupled model tends to underestimate the PMF in case of low spatio-temporal variability of the precipitation input, although one of the three hydrographs shown in this plot is the reference estimation itself.

Figure 4.5 shows the influence of the spatio-temporal PMP representation on the hydrograph that defines the respective PMF estimation. A uniformly distributed PMP leads to PMF estimations below the reference scenario. The PMF estimations resulting from a PMP distributed using the hyetograph method are highly variable and lie below as well as above the reference scenario. The PMP distributed using a Monte Carlo-method generally leads to relatively high estimations. In comparison to the reference estimation, the method tends to overestimate the PMF when it is not applied with a model with corresponding spatial and temporal discretisation.

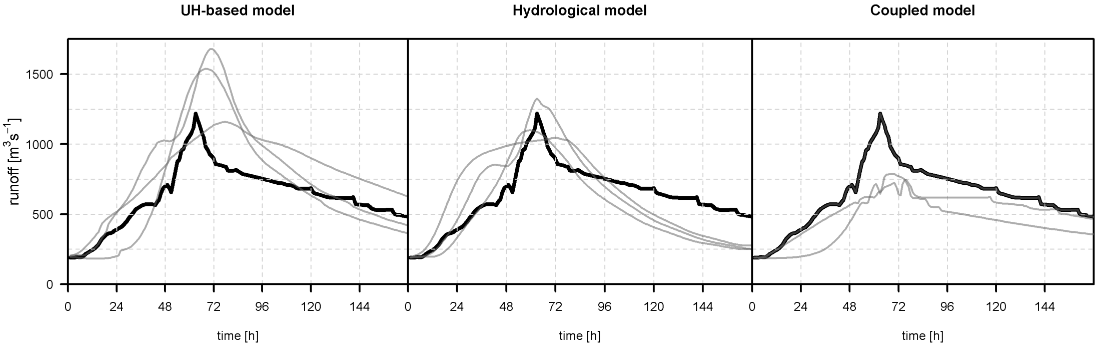


Figure 4.4: In grey, the highest hydrographs generated by the method combinations, sorted by modelling approach. The peaks of the hydrographs indicate the corresponding PMFs. The differences in the hydrographs are attributable to the varying spatio-temporal PMP distributions applied. The bold black line represents the reference hydrograph (Monte Carlo PMP distribution, coupled model).

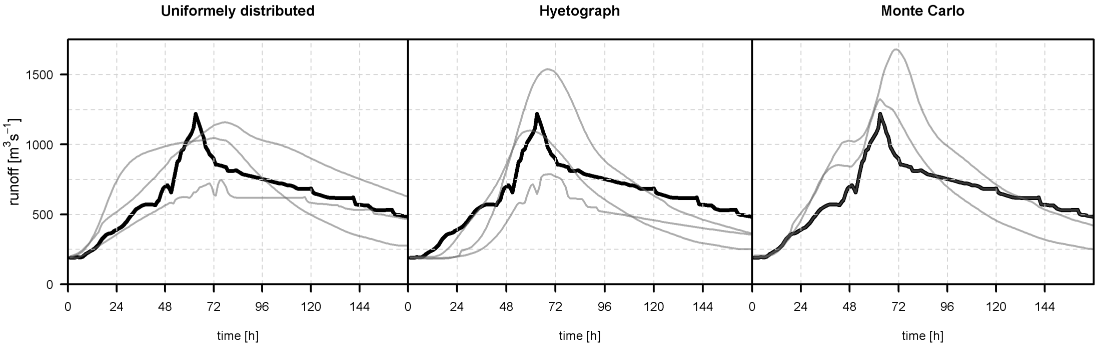


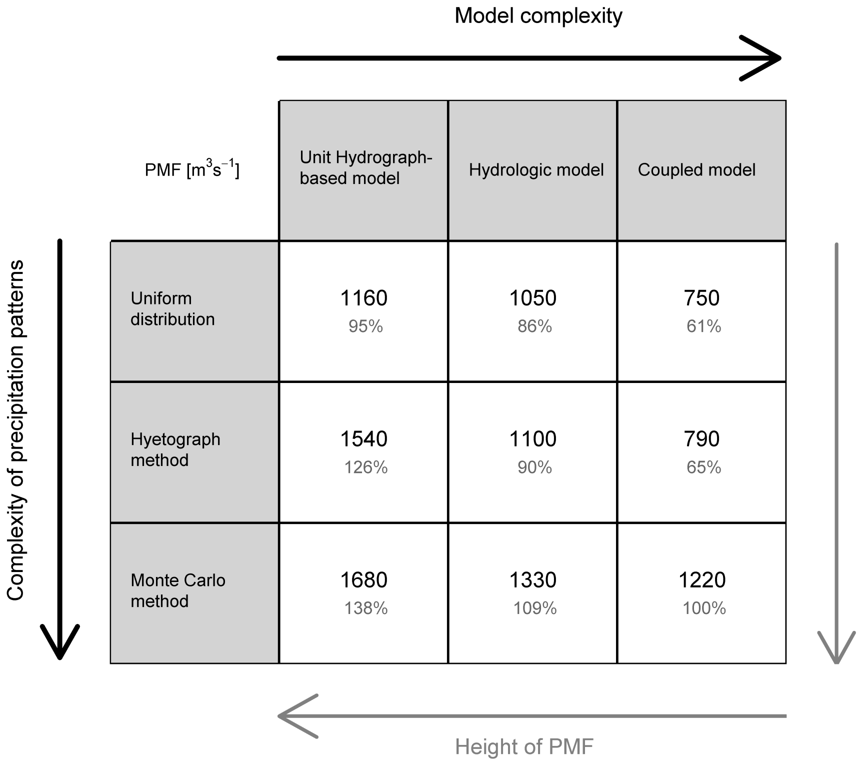
Figure 4.5: In grey, the highest hydrographs generated by the method combinations, sorted by spatio-temporal PMP representation. The peaks of the hydrographs indicate the corresponding PMFs. The differences in the hydrographs are attributable to the varying modelling approaches applied. The bold black line represents the reference hydrograph (Monte Carlo PMP distribution, coupled model).

4.5 Discussion

An overview on the PMF estimations that result from the combinations of PMP distribution approaches and modelling approaches is shown in Fig. 4.6. Two tendencies are remarkable. Regarding the spatio-temporal representation of the PMP, the application of a more complex method leads to a higher PMF estimation. Regarding the modelling approaches, the application of a more complex model generally leads to a lower PMF estimation.

4.5.1 Influence of the spatio-temporal PMP representation

The complexity of the spatio-temporal PMP distribution coincides with the height of the corresponding PMF estimation. A uniform PMP distribution in space and time does not maximize the catchment reaction, which aligns with the findings of Seo et al. (2012). Compared to the reference PMF estimation, the uniform PMP distribution method leads to a significant underestimation of the PMF. Moreover, such a distribution lacks consistency with observed storm patterns. The value of a uniform distribution lies in its relatively simple and efficient generation procedure, as well as in the simple application of the pattern in any model. The second PMP distribution method under consideration, the hyetograph method, demonstrates a higher spatio-temporal PMP variability than the uniform PMP distribution method. The hyetograph method generates arrangements that lead to both lower and higher peak discharges than the uniform distribution does. As only the highest peak discharge defines the PMF, the hyetograph distribution leads to a higher PMF estimation than the uniform distribution. The highest degree of variability in space and time, as well as the highest number of scenarios, is generated with the Monte



PMF [m^3s^{-1}]	Unit Hydrograph-based model	Hydrologic model	Coupled model
Uniform distribution	1160 95%	1050 86%	750 61%
Hyetograph method	1540 126%	1100 90%	790 65%
Monte Carlo method	1680 138%	1330 109%	1220 100%

Figure 4.6: Resulting PMF estimates of all combinations of the three spatio-temporal PMP representations and the three applied modelling approaches.

Carlo method. This allows for the consideration of more possible distributions that could maximize the catchment reaction, leading to the highest PMF estimations.

These findings can be generalized to a certain degree. However, the specific influence of the spatio-temporal precipitation distribution on the PMF estimation is catchment-specific. Recent studies have shown that the influence of rainfall variability on flood response depends on catchment size, catchment characteristics and runoff generation processes (Nicótina et al., 2008; Adams et al., 2012; Lobligeois et al., 2014; Paschalis et al., 2014; Emmanuel et al., 2015). These effects may accentuate or mask the general implications of the choice of a spatio-temporal PMP representation that are described above. As the discharge-maximizing PMP distribution is not known *a priori*, it is reasonable to incorporate as many and as varying spatio-temporal PMP distributions as the available data allow, provided that the distributions are physically plausible. This reduces the chance of missing a discharge-maximizing spatio-temporal distribution.

4.5.2 Influence of the modelling approach

The ways that the models differently consider and represent physical processes explain why increased model complexity lowers PMF estimation. The UH-based model converts the incoming precipitation relatively directly to catchment outflow. Besides the effect of the lakes, which is considered in the UH-model applied in this study, the model simulates no additional processes that could lower peak discharge. In contrast, the hydrologic model deterministically incorporates retentive factors e.g. soil moisture storages, groundwater storages and interflow storages. Regarding extreme precipitation inputs, these storages have retentive effects that, in sum, reduce peak discharge at the catchment outflow. The coupled model additionally captures the most relevant retention processes resulting from inundation and the storage of water masses on floodplains that are not considered in the hydrologic model. This has an additional effect of lowering peak discharge. It can be stated that an increasing model complexity also increases the representation of physical processes. This more accurate representation of physical processes dampens the modelled peak discharge and therefore the PMF estimation.

Although the different modelling approaches lead to systematically different estimations, the magnitude of the difference attributable to the modelling approach is expected to be catchment specific. This is due to varying decisive flood-triggering processes (Paschalis et al., 2014), varying channel network topology (Moussa, 2008) and the varying presence of lakes and artificial structures. Besides the actual differences in catchment behaviour, the representation of the mentioned effects in a model depends on the model's structure (Vansteenkiste et al., 2014).

As is the case with the peak-discharge-maximizing spatio-temporal precipitation distributions, the decisive flood-triggering and peak-discharge-dampening processes are also not known *a priori*. This calls for the application of a model that incorporates as many potentially decisive processes as possible, hence for the appliction of a model as sophisticated as the available data allow for.

4.5.3 Combined influence

The modelling approach and the spatio-temporal PMP representation have a strong influence on the resulting PMF estimation. The choices of a modelling approach and a spatio-temporal PMP representation approach should be coordinated in order to avoid adverse combinations. Particularly the use of a highly sophisticated model with a relatively coarse spatio-temporal PMP representation should be avoided, as such an application tends to underestimate the PMF. In contrast, the use of a basic and straightforward model fed with highly variable precipitation patterns tends to overestimate the PMF and should therefore also be avoided.

4.6 Conclusions

Three different spatio-temporal PMP representations were fed into three different models in order to estimate the PMF for an alpine catchment. The nine resulting PMF estimations vary distinctively. One main reason for the differences in the PMF estimations is the varying degree of spatio-temporal variability of the PMP representations. The PMF estimation increases with increasing variability in the spatio-temporal distribution of the precipitation input. The second main reason for the differences in the PMF estimations is the varying representation of physical processes in the applied modelling approaches. The PMF estimation decreases with increasing model complexity due to the increasing number of physical processes that are captured by the applied model. The results of this study show that the choice of spatio-temporal PMP representation and the choice of modelling approach should be carried out in a balanced way such that they are compatible with each other.

The PMP distribution approach and the PMF modelling approach should be chosen based on a study's aim and on the availability of data and expertise, provided the modelling approach and the spatio-temporal PMP representation are consistent and of similar complexity. The application of a basic UH-based model fed with a uniformly distributed PMP enables a rough PMF estimation. The use of a hydrologic model for PMF estimation fed with hyetograph PMP patterns can be seen as a compromise between detail and computational efficiency. However, important processes like floodplain retention are still neglected using both of the aforementioned options. Thus, in cases where highly reliable estimation is required, e.g. for insurance purposes or for the planning of sensitive infrastructure, a more sophisticated estimation approach is recommended, as decisive physical processes can influence the result remarkably. PMF estimation is of high relevance in most cases; therefore it is reasonable to strive for the most sophisticated modelling approach. In all cases, the mutual influence of the complexity of precipitation patterns and the complexity of the applied model must be accounted for to avoid a notable under- or overestimation of the PMF.

Acknowledgements

We would like to thank Anne de Chastonay and Ole Rössler for improving the manuscript. The Department for Water and Waste of the Canton of Bern (AWA), the Swiss Federal Office of Environment (FOEN) and the Swiss Federal Office for Meteorology (MeteoSwiss) are thanked for providing geospatial, hydrological and meteorological data.

Funding

This study is funded by the Mobiliar Lab for Natural Risks.

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5 Synthese

Die Abschätzung extremer Hochwasser, welche beobachtete Ereignisse deutlich übersteigen, stellt methodisch eine grosse Herausforderung dar. Angesichts der grossen Relevanz von Extremhochwasserabschätzungen ist es wichtig, dass bestehende Methoden stets kritisch hinterfragt, weiterentwickelt und miteinander verglichen werden. Dies ermöglicht eine begründete Auswahl der jeweils geeignetsten Werkzeuge für eine Extremhochwasserabschätzung unter Berücksichtigung des verfolgten Zieles und der vorhandenen Ressourcen.

In der vorliegenden Arbeit wurde als erstes eine neue Methode zur Berechnung der räumlich-zeitlichen Niederschlagsverteilung eingeführt. Im zweiten Teil wurde eine relativ neue und in diesem Zusammenhang wenig erforschte Methode zur Niederschlag-Abfluss-Modellierung, nämlich die Kopplung hydrologischer und hydraulischer Modelle, für den Extremhochwasserbereich getestet und deren Mehrwert gegenüber der herkömmlichen deterministischen Modellierung untersucht. In einem dritten Teil wurden schliesslich drei verfügbare Methoden zur räumlich–zeitlichen Niederschlagsverteilung, inklusive der neu eingeführten Methode aus dem ersten Teil, und drei Ansätze der Niederschlag-Abfluss-Modellierung systematisch getestet und bewertet.

In diesem abschliessenden Kapitel wird zuerst ein Überblick über die Resultate und die gewonnenen Erkenntnisse gegeben. Darauf folgt eine Betrachtung des Mehrwertes sowie der Grenzen methodischer Weiterentwicklungen hinsichtlich einer plausiblen und robusten Extremhochwasserabschätzung. Schliesslich wird der Bezug zum Konzept der statistischen Herleitung von Wiederkehrperioden und zum integralen Risikomanagements hergestellt.

5.1 Zusammenfassung der Resultate

Niederschlagsverteilung

Es wurde ein Verfahren entwickelt, um aus den anhand der Richtlinien der WMO (2009) erstellten Abschätzungen des PMP-Niederschlages physikalisch plausible Niederschlagsinputs für eine PMF-Abschätzung herzuleiten. In einem mehrstufigen Verfahren wurden zahlreiche räumlich-zeitliche Verteilungen des PMP-Niederschlages generiert und hinsichtlich ihrer physikalischen Plausibilität geprüft. Die Entwicklung und Anwendung eines effizienten hydrologischen Modelles ermöglichte die Modellierung einer grossen Anzahl so generierter räumlich-zeitlicher Verteilungen des PMP-Niederschlages in einem Monte-Carlo-Verfahren. Anhand der modellierten Szenarien konnten diejenigen räumlich-zeitlichen Verteilungen identifiziert werden, welche die höchsten Spitzenabflüsse zur Folge haben und daher einer eingehenderen Untersuchung bedurften. Als Nebenprodukt konnte der Spitzenabfluss eines PMF-Hochwassers für das Einzugsgebiet der Aare bis Bern auf den Bereich zwischen 800 und 1600 m^3 s^{-1}, mit einer medianen Schätzung von rund 1200 m^3 s^{-1}, eingegrenzt werden. Ein Vergleich mit gemessenen Hochwasserspitzen sowie mit den Resultaten vorliegender Hochwasserstudien im Einzugsgebiet zeigte, dass diese erste Approximation des PMF-Hochwassers in einem plausiblen Bereich liegt.

Schliesslich wurde die Sensitivität des Spitzenabflusses bezüglich der räumlichen und der zeitlichen Niederschlagsverteilung untersucht. Dabei zeigte sich, dass Puffer innerhalb des Einzugsgebietes, beispielsweise in Form von Seen, die Auswirkungen bestimmter räumlich-zeitlicher Niederschlagsverteilungen deutlich beeinflussen können. Hohe Spitzenabflüsse aus einem Einzugsgebiet werden tendenziell eher dann erreicht, wenn ein relativ grosser Anteil des Ereignisniederschlages auf Gebiete fällt, welche direkt und ohne Durchlaufen eines puffernden Speichers zum Abfluss aus einem Einzugsgebiet beitragen.

Modellkopplung

Anhand eines Experiments wurde die Existenz von Grenzwerten für ein nicht-lineares Einzugsgebietsverhalten aufgrund von Überschwemmungs- und Retentionseffekten dargelegt. Für das Testeinzugsgebiet wurden sogenannte synthetische Bemessungsganglinien (synthetic design hydrographs, kurz SDH) hergeleitet und in ein hydraulisches Modell eingespiesen. Bis zu einem Spitzenabfluss, welcher ungefähr einem HQ_{100} entspricht, zeigten die modellierten Abflussganglinien am Gebietsausfluss verglichen mit den eingespiesenen SDH-Ganglinien, abgesehen von einer geringfügigen zeitlichen Verzögerung aufgrund der Fliessdauer, keine Beeinträchtigung. Im Falle von grösseren Spitzenabflüssen zeigten sich mehrere deutliche Schwellenwerte, deren Überschreitung die Erschliessung grossräumiger Überflutungsflächen zur Folge hat. Das Überschreiten eines solchen Schwellenwertes hat einen abmindernden Effekt auf den Spitzenabfluss am Gebietsausfluss.

Die zur Kalibrierung hydrologischer Modelle verwendeten Daten umfassen in der Regel keine Abflüsse, welche einem PMF-Spitzenabfluss nahe kommen. Sie enthalten demnach auch keine Informationen über Prozesse, welche nach Überschreitung bestimmter Schwellenwerte jenseits des grössten gemessenen Hochwassers auftreten. Hydrologische Modelle sind daher nicht in der Lage, den Einfluss grossräumiger Retentionseffekte bei einem möglichen PMF-Ereignis abzubilden. Die Kopplung von hydrologischen und hydraulischen Modellen dagegen erlaubt eine realistischere Modellierung der Einzugsgebietsreaktion auf den PMP-Niederschlag. Die Modellierung von 100 PMP-Niederschlagsszenarien aus dem ersten Teil der Arbeit, sowohl mit einem hydrologischen Modell als auch mit einem gekoppelten hydrologisch-hydraulischen Modell, bestätigte den Einfluss dieses Effektes auf eine PMF-Abschätzung. Die mit dem gekoppelten Modell berechneten Ganglinien bilden den Einfluss von Überschwemmungs- und Retentionseffekten und die daraus folgende Abminderung des Spitzenabflusses plausibel ab. Diese Abminderung ist in den aus dem hydrologischen Modell resultierenden Ganglinien nicht zu beobachten.

Methodenvergleich

Das Kapitel 4 beinhaltet einen systematischen Vergleich von verschiedenen in der Praxis angewandten Methoden zur Abschätzung des PMF-Hochwassers. Die räumlich-zeitliche Verteilung des PMP-Niederschlages wurde mittels dreier Methoden von unterschiedlicher Komplexität, und unterschiedlicher daraus resultierender Variabilität, vorgenommen. Die Modellierung der Einzugsgebietsreaktion auf den PMP-Niederschlag wurde mit drei verschiedenen Modellierungsansätzen unterschiedlicher Komplexität vorgenommen. Aus der Kombination von drei verschiedenen räumlich-zeitlichen Verteilungen des PMP-Niederschlages und drei verschiedenen Modellierungsansätzen resultierten schliesslich neun PMF-Abschätzungen, welche untereinander verglichen werden konnten. Die Resultate zeigten auf, dass die Wahl der Methoden die resultierende PMF-Abschätzung deutlich beeinflussen kann. Dabei konnte in zweierlei Hinsicht ein Muster identifiziert werden:

1. Je höher die Komplexität und Variabilität der in ein Modell eingespiesenen Niederschlagsverteilung, desto höher liegt die daraus resultierende PMF-Abschätzung. Der einfachste Fall ist dabei die Anwendung einer gleichmässigen Verteilung des Gesamtniederschlags über die einzelnen Zeitschritte und über die Einzugsgebietsfläche. Die grösste Variabilität dagegen wird durch die Anwendung eines Monte-Carlo-Ansatzes erreicht. Die Berücksichtigung aller möglichen räumlich-zeitlichen Verteilungen bedeutet, dass die den Abfluss maximierende Verteilung berücksichtigt ist.

2. Je komplexer die Struktur des verwendeten Niederschlag-Abfluss-Modelles, desto niedriger fällt die daraus resultierende PMF-Abschätzung aus. Eine höhere Komplexität in der Modellstruktur führt im Optimalfall zu einer detaillierteren Berücksichtigung der Prozesse innerhalb des Einzugsgebietes (e.g. das Auffüllen von Bodenfeuchte- und Grundwasserspeicher sowie von Überflutungs- und Retentionsräumen), was in der Summe einen abmindernden Effekt auf die geschätzte Abflussspitze hat.

Die resultierenden PMF-Abschätzungen für die Aare in Bern lagen zwischen 750 und 1680 m^3 s^{-1}. Die als am verlässlichsten beurteilte Schätzung, resultierend aus der Kombination der jeweils anspruchsvollsten Methoden, lag bei 1220 m^3 s^{-1}.

Die Methodenwahl basiert in den meisten Fällen auf der Verfügbarkeit finanzieller, materieller und zeitlicher Ressourcen. Mit dem systematischen Vergleich verschiedener Methodenkombinationen konnte gezeigt werden, dass auch die Konsistenz der gewählten Methoden beachtet werden muss. Konkret bedeutet das, dass die Wahl der Methode zur räumlich-zeitlichen Verteilung des PMP-Niederschlages und die Wahl des Modellierungsansatzes aufeinander abgestimmt sein muss, um eine markante Über- oder Unterschätzung des PMF-Hochwassers zu vermeiden. Eine grobe Abschätzung des PMF-Hochwassers kann dabei mit relativ einfach anzuwendenden Methoden bewerkstelligt werden. Wenn eine grobe Abschätzung in Bezug auf die Fragestellung nicht ausreichend ist, empfiehlt sich die Anwendung komplexerer Methoden. Diese weisen eine grössere Prozessnähe auf und liefern daher im physikalischen Sinne plausiblere Resultate.

5.2 Mehrwert methodischer Weiterentwicklungen

Niederschlagsverteilung

Grundsätzlich ist gemäss den Vorgaben der WMO (2009) der Niederschlag so über dem Einzugsgebiet zu verteilen, dass der daraus resultierende Abfluss maximiert wird. Die Berücksichtigung von komplexen, sprich räumlich und zeitlich hoch variablen Niederschlagsverteilungen begünstigt im Vergleich zu weniger komplexen, beispielsweise gleichverteilten Niederschlagsmustern eine weitere Maximierung der Abflussspitze. In dieser Hinsicht ist die Berücksichtigung immer komplexerer Niederschlagsverteilungen anzustreben. Die angewandten Methoden zur Verteilung des PMP-Niederschlages unterscheiden sich jedoch nicht nur in ihrer Komplexität, sondern auch in ihrer physikalischen Plausibilität. Das bedeutet, dass eine Niederschlagsverteilung nicht beliebig angeordnet werden kann, sondern eine gewisse Nähe zur Struktur von gemessenen Ereignissen aufweisen soll. Die Frage, wie realitätsnah oder -fern eine das PMF-Hochwasser maximierende Niederschlagsverteilung sein darf, ist letztlich philosophischer Natur.

Modellkopplung

Die Anwendung eines gekoppelten hydrologisch-hydraulischen Modelles führt gegenüber der alleinigen Anwendung eines hydrologischen Modelles zu einer deutlich plausibleren und besser nachvollziehbaren Schätzung. Plausibilität und Nachvollziehbarkeit sind insbesondere von Bedeutung, wenn eine PMF-Schätzung zum Schutz sensitiver Infrastruktur beitragen soll.

Neben einer physikalisch plausibleren PMF-Abschätzung hat die Anwendung eines hydraulischen Modelles gegenüber der alleinigen Anwendung eines hydrologischen Modelles noch weitere Vorteile. Die Anwendung eines hydraulischen Modelles ermöglicht die Erfassung von im Ereignisfall betroffenen Flächen, und damit die Abschätzung des potentiellen Schadens eines PMF-Hochwassers, wie es von Ward u. a. (2011) vorgeschlagen wurde.

In Kombination mit einer Vielzahl an PMP-Verteilungen ermöglicht die Anwendung eines hydraulischen Modelles eine Zuweisung einer Überflutungswahrscheinlichkeit im PMF-Fall, wie in Abb. 5.1 dargestellt. Die hydrologisch-hydraulische Modellierung einer grossen Anzahl von PMP-Niederschlagsszenarien resultiert in einer ebenso grossen Anzahl an variierenden Überflutungskarten. Für jeden in einem hydraulischen Modell repräsentierten Punkt kann durch eine Überlagerung der resultierenden Karten analysiert werden, bei welchem Anteil aller berücksichtigten räumlich-zeitlichen PMP-Niederschlagsverteilungen eine Überflutung auftritt. Dies unter der Annahme, dass alle Niederschlagsverteilungen gleich wahrscheinlich sind. In Kombination mit Informationen über Fliesstiefe und -geschwindigkeit sowie einem Schadensmodell liesse sich schliesslich der PMF-induzierte Schaden probabilistisch beschreiben (Botto u. a., 2014).

Die Überlagerung von Überflutungskarten verschiedener PMF-Szenarien ist exemplarisch in Abb. 5.2 dargestellt. Daraus geht hervor, dass die meisten Gebäude im Kartenausschnitt nur von wenigen PMF-Szenarien betroffen sind. Das Beispiel zeigt auf, dass die Wahl der räumlich-zeitlichen Verteilung des Niederschlages das Ausmass der modellierten Überflutungen, und demnach auch die darauf basierende Schadensabschätzung beeinflusst. Die Berücksichtigung einer grossen Anzahl von Szenarien ermöglicht eine Schadensschätzung, welche nicht von der Wahl einer einzigen räumlich-zeitlichen Verteilung des Niederschlages abhängt.

Methodenvergleich

Die meisten der in der vorliegenden Arbeit berücksichtigten Kombinationen von Niederschlagsverteilungen und Modellierungsansätzen wurden in den vergangenen Jahren in Wissenschaft oder Praxis für PMF-Studien verwendet. Die meist fehlende Begründung der Methodenwahl deutet darauf hin, dass der Einfluss der Methodenwahl auf das Resultat tendenziell unterschätzt wird. In der vorliegenden Arbeit konnten verschiedene Ansätze unter hinsichtlich Einzugsgebiet, Gesamtniederschlag und Initialbedingungen identischen Rahmenbedingungen angewandt und miteinander verglichen werden. Dabei wurde bei jeder berücksichtigten Methode auf eine bestmögliche Umsetzung geachtet. Die Auswahl der berücksichtigten Methoden ist nicht abschliessend, und eine Evaluation weiterer Methoden ist wünschenswert. Nichtsdestotrotz liefert der Methodenvergleich Informationen sowohl zu der besagten Methodenabhängigkeit an sich, als auch auf die Grössenordnung dieses Effektes in Bezug auf eine PMF-Abschätzung.

Ein Entscheid zur Auswahl einer Methode ist meist einhergehend mit einem Entscheid zu damit verbundenen methodischen Vor- und Nachteilen. Die Resultate machen deutlich,

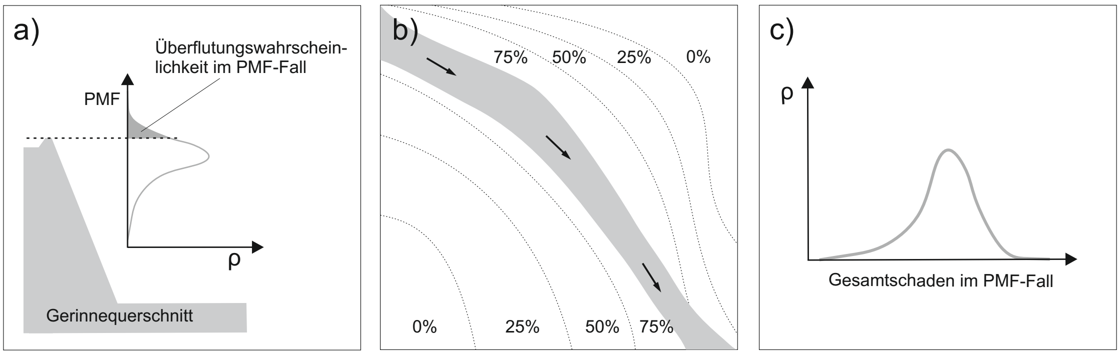


Abbildung 5.1: Schematische Darstellung einer möglichen Zuweisung von PMF-Risiken und einer darauf basierenden Schadensschätzung unter der Annahme, dass alle berücksichtigten räumlich-zeitlichen Verteilungen des PMP-Niederschlages gleich wahrscheinlich sind.
a) Die modellierten Spitzenabflüsse des PMF-Hochwassers variieren aufgrund verschiedener räumlich-zeitlicher Niederschlagsverteilungen. Aus diesen Spitzenabflüssen kann für jeden Gerinnequerschnitt die Anzahl Überschreitungen der Gerinnekapazität und damit die Überflutungswahrscheinlichkeit im PMF-Fall bestimmt werden.
b) Aus einer Überlagerung der Überflutungskarten für jedes PMF-Szenario kann für jeden Punkt in der Karte die Wahrscheinlichkeit einer Überflutung sowie der erwarteten mittleren Fliesstiefe im PMF-Fall abgeleitet werden. Die Abbildung zeigt schematisch die Isolinien der Überflutungswahrscheinlichkeit im PMF-Fall für vier Quartile.
c) Aus einer Kombination der Daten aus b) und einer Schadenfunktion resultiert eine Dichtefunktion, welche den erwarteten Gesamtschaden im Falle eines PMF-Hochwassers beschreibt.

dass eine Methode im Allgemeinen und ein Modell im Speziellen stets ein Werkzeug zur Annäherung an reale Vorkommnisse darstellt. Die in dieser Arbeit gewonnenen Erkenntnisse können zukünftigen Studien zu Extremhochwassern als Grundlage für eine wohlüberlegte und der Zielgrösse angepasste Methodenwahl dienen.

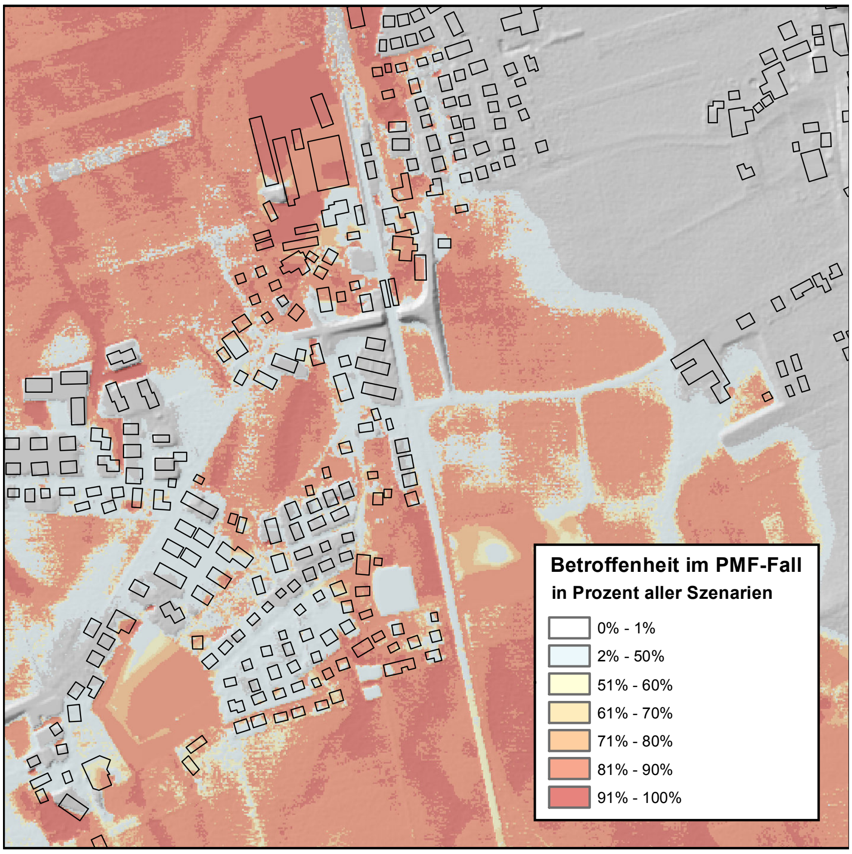


Abbildung 5.2: Die Wahrscheinlichkeit einer Überflutung im PMF-Fall im südlichen Teil der Gemeinde Wichtrach BE. Aus der räumlichen Analyse von PMF-Szenarien und Portfolio-Daten kann eine probabilistische Abschätzung der Schäden eines PMF-Hochwassers vorgenommen werden.

5.3 Ausblick

5.3.1 Verbesserungspotential im methodischen Bereich

Im Bereich der räumlich-zeitlichen Niederschlagsverteilung konnte mit dem vorgestellten Monte-Carlo-Ansatz ein Schritt hin zur konsequenteren Nutzung der verfügbaren Ressourcen und Methoden aufgezeigt werden. Es ist zu erwarten, dass in Zukunft sowohl in methodisch-statistischer Sicht, als auch im Bereich der Rechenleistung weitere Fortschritte erzielt werden. Dies erlaubt eine fortlaufende Prüfung neuer Ansätze und Methoden zur PMF-Abschätzung.

Insbesondere im Bereich der räumlichen und zeitlichen Abhängigkeiten in Niederschlagsfeldern stehen bereits jetzt weitere zu prüfende Konzepte bereit (z.B. Bennett u. a., 2016). Eine Möglichkeit, um räumlich-zeitliche Abhängigkeiten noch besser abzubilden, ist beispielsweise die Prüfung der physikalischen Plausibilität von Monte-Carlo-erzeugten

Niederschlagsfeldern mit komplexeren statistischen Verfahren. Die Grundidee dabei ist es, die Struktur von extremen Niederschlagsereignissen statistisch zu beschreiben, und mit der Struktur der generierten Verteilung abzugleichen. Die Struktur von beobachteten Niederschlagsverteilungen kann beispielsweise mittels eines Kataloges von Semivariogrammen, oder mittels multivariater Copula-Funktionen beschrieben werden. Die Ähnlichkeit einer generierten Niederschlagsverteilung zum statistisch beschriebenen Referenzdatensatz kann als Mass für die Plausibilität herangezogen werden. Auf diese Weise kann unter anderem der Einfluss orographischer Effekte direkt miteinbezogen werden.

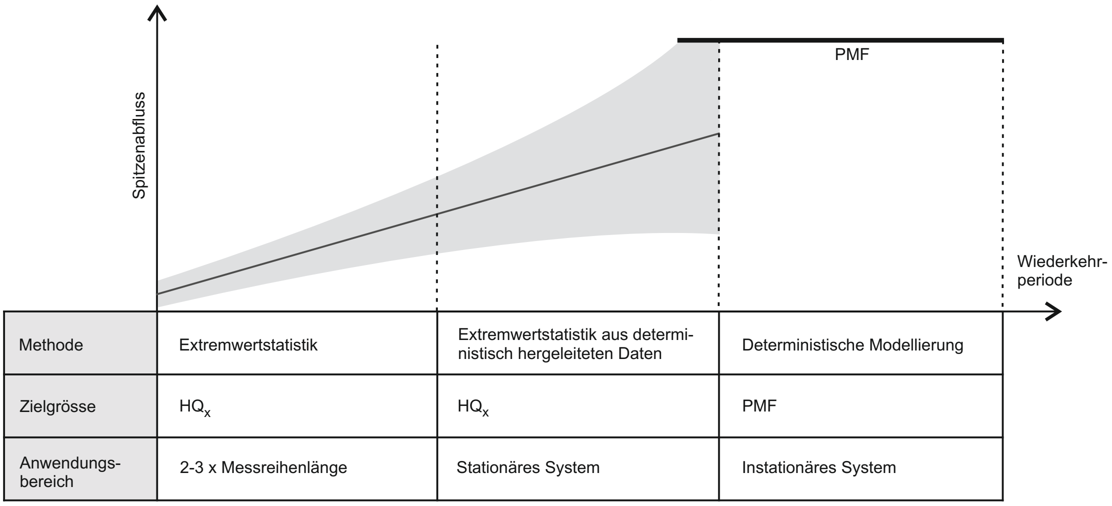
Auch im Bereich der hydrologisch-hydraulischen Modellierung ist mit Weiterentwicklungen zu rechnen. Dies einerseits aufgrund der fortlaufenden Optimierung bestehender Modelle, und andererseits aufgrund der weiterhin zunehmenden verfügbaren Rechenkapazität. Dies ermöglicht einen deterministischen Miteinbezug von Szenarien für weitere nicht-lineare Prozesse, auf welche in der vorliegenden Arbeit nicht näher eingegangen werden konnte. Beispiele für solche Prozesse sind die Erosion und Ablagerung von Sedimenten, der Transport von Geschiebe und Schwemmholz, das Auftreten von Verklausungen und durch Verklausungen induzierte Rückstaueffekte, sowie grossräumige morphologische Gerinneänderungen.

Für plausible und verlässliche Abschätzungen von Extremhochwassern sind demnach weitere Vergleichsstudien sowohl bezüglich der räumlich-zeitlichen Repräsentation eines PMP-Niederschlages, als auch bezüglich verwendeter Modellierungsansätze sinnvoll.

5.3.2 Der Weg zu einer skalenübergreifenden Hochwasserabschätzung

Die spezifischen Anwendungsbereiche von statistischen, deterministischen, und kombinierten Methoden gelten oftmals als Barriere für eine skalenübergreifende Hochwasserabschätzung, welche von der Schätzung eines Jahreshochwassers bis hin zur Schätzung eines PMF-Hochwassers reicht. Weder statistische, deterministische, noch kombinierte Methoden vermögen alleine für die ganze Bandbreite plausible und robuste Schätzungen zu liefern. Es bietet sich daher an, für jeden Bereich auf der Jährlichkeitsskala einzugsgebietsspezifisch die geeignetste Methodik anzuwenden, und die daraus resultierenden Abschätzungen zu einem Gesamtbild zu kombinieren. Eine solche Kombination ist in Abb. 5.3 schematisch dargestellt. Eine extremwertstatistische Analyse der Jahreshochwasser HQa erlaubt eine Hochwasserabschätzung im besten Fall bis zu einer Jährlichkeit, die dem zwei- bis dreifachen der Messreihenlänge entspricht (Coles, 2004). Das bedeutet, dass der Anwendungsbereich dieser Methode abhängig von der Länge der verfügbaren Messreihe ist und damit je nach Einzugsgebiet variiert.

Die Abschätzung von Bemessungshochwassern über dieser Grenze bedarf einer Extremwertstatistik, welche auf einer erweiterten Stichprobe beruht. Die Erweiterung der



Methode	Extremwertstatistik	Extremwertstatistik aus deterministisch hergeleiteten Daten	Deterministische Modellierung
Zielgrösse	HQ_x	HQ_x	PMF
Anwendungs-bereich	2-3 x Messreihenlänge	Stationäres System	Instationäres System

Abbildung 5.3: Schematische Darstellung des vorgeschlagenen Anwendungsbereiches verschiedener Methoden in der Extremhochwasserabschätzung. Die vertikalen Linien begrenzen jeweils den Anwendungsbereich einer Methode. Ihre Lage bezüglich der Wiederkehrperiode ist dabei sowohl von Verfügbarkeit und Qualität hydrologischer Daten als auch von Einzugsgebietscharakteristika abhängig.

Stichprobe kann mittels historischer oder kausaler Informationserweiterung, oder mittels stochastisch-deterministischer Erzeugung einer langen Messreihe, etwa durch Gebrauch eines stochastischen Wettergenerators und anschliessender hydrologischer Modellierung, geschehen. Diese Methoden ermöglichen es, auch Hochwasser jenseits der methodischen Grenze aufgrund der Messreihenlänge abzuschätzen, wenn auch mit markant grösserem Unsicherheitsbereich. Die Extremwertstatistik basierend auf einer erweiterten Stichprobe kann plausible Schätzungen liefern, solange die Bedingung der Stationarität des Einzugsgebietes erfüllt ist. Der Bereich jenseits dieser Grenze, beispielsweise aufgrund sich ändernder Fliesswege (vgl. Rogger u. a., 2012) oder aufgrund des Einflusses grossräumiger Retentionsräume (vgl. Kapitel 3), ist mit extremwertstatistischen Methoden nur bedingt und mit sehr grossen Unsicherheiten abzubilden (vgl. Sivapalan und Samuel, 2009; Obeysekera und Salas, 2014; Salas und Obeysekera, 2014; Serinaldi und Kilsby, 2015; Obeysekera und Salas, 2016). Auch diese Grenze des methodischen Anwendungsbereiches ist Einzugsgebietsspezifisch.

Für die Abschätzung extremer Hochwasser, bei welchen das Einzugsgebiet aufgrund verschiedener Prozesse nicht mehr stationär ist, sollte die Schätzung eines Bemessungshochwassers durch die Angabe einer Obergrenze in Form des PMF-Hochwassers ersetzt werden. Die daraus resultierenden Annäherungen an die Zielgrösse sind dabei stets kritisch zu hinterfragen.

Ein erster Schritt dazu ist ein Vergleich zwischen deterministischer und deterministisch-statistischer Abschätzung eines Extremhochwassers auf dem jeweils aktuellsten Stand von Methoden und Technik. Konkret wird ein Vergleich zwischen einer Schätzung des $HQ_{10\,000}$ auf dem aktuellsten Stand von Methoden und Technik, wie beispielsweise der SCHADEX-Methode (Paquet u. a., 2013), mit einer ebensolchen Schätzung des PMF-Hochwassers, jeweils unter Verwendung der gleichen Modelle und der gleichen Initialbedingungen, empfohlen.

5.3.3 Abschliessende Bemerkungen

Es ist damit zu rechnen, dass in Zukunft sowohl die Rechenkapazität an sich als auch deren Verfügbarkeit weiter zunehmen wird. Weiter sind im Bereich der Modellentwicklung und Modellverfügbarkeit weitere Fortschritte absehbar. Dies hat zur Folge, dass die Abschätzung extremer Hochwasser mittels komplexer Methoden und Modelle in Zukunft mit einem geringeren Einsatz an zeitlichen, personellen und finanziellen Ressourcen möglich sein wird, als dies aktuell der Fall ist. Eine ständige methodische Weiterentwicklung ist notwendig, um aus dem jeweils aktuellen Stand der Technik das Optimum für eine physikalisch fundierte und plausible Extremhochwasserabschätzung zu erreichen.

Die Umsetzung des integralen Risikomanagements sollte sich dabei stets an den verfügbaren methodischen Möglichkeiten orientieren. Die genaue Festlegung eines Schutzziels basierend auf einer bestimmten Wiederkehrperiode ist nur dann sinnvoll, wenn Datengrundlagen und Methoden eine plausible Abschätzung des entsprechenden Szenarios erlauben. Die obere Grenze einer sinnvollen Zuweisung von Wiederkehrperioden zu Abflussspitzen ist dabei von Einzugsgebiet zu Einzugsgebiet verschieden.

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Danksagung

An dieser Stelle möchte ich mich bei allen bedanken, welche zum Gelingen dieser Arbeit beigetragen haben:

Rolf Weingartner, für die grossartige Begleitung und Unterstützung während aller Phasen der Arbeit.

Allen angehörigen der Gruppe für Hydrologie und des Mobiliar Lab für Naturrisiken, für die angeheme Arbeitsatmosphäre, die anregenden Diskussionen und die geselligen Momente. Ein spezieller Dank geht an Martina Kauzlaric, Ole Rössler, Jan Schwanbeck und Andreas Zischg für das Lösen modelltechnischer Rätsel, das Einbringen neuer Ideen und die hilfreichen Ratschläge, sowie an Tom Reist für die zahlreichen Arbeiten im Hintergrund, dank denen so manches viel leichter fällt.

Meinem Freundeskreis und meinen Weggefährten während des Studiums, welche mich immer wieder antrieben oder abbremsten, je nach dem, was gerade nötig war. Speziell bedanken möchte ich mich bei den GIUB-Mitinsassen Pascal Hänggi, Elias Hodel und Fabia Hüsler, sowei bei meinen ehemaligen Mitbewohnern Elisabeth Dürr, Marius Moser, Marc Peier und Silvan Vogel.

Meiner Familie, auf deren bedingungslose Unterstützung ich immer zählen konnte.

Anne de Chastonay, für die grossartige Zeit, die hinter uns liegt, und für die grossartige Zeit, die wir noch vor uns haben.