NTNU – Trondheim
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Furthering the representation of causal chains between water and land use in Life Cycle Assessment

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Master of Energy and Environmental Engineering

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MASTER THESIS

for

Student
Martin Moxnes

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Furthering the representation of causal chains between water and land use in Life Cycle Assessment

Videreutvikling av representasjon av årsakssammenhenger mellom vann- og landbruk i Livssyklusanalyse

Background and objective

In recent years the development of methodologies for assessing impacts from land and water use on ecosystems and human health has made very large progress. However, both resources are still treated individually, neglecting links between the two, even though they are closely interrelated in reality. An example is deforestation, which does not only lead to an impact in terms of land use, but also has implications for the microclimate and hydrological cycle. On one hand evapotranspiration from trees will be reduced and less water consumed, but on the other hand water retention capacities could be reduced and erosion favoured, potentially leading to higher and faster peak flows in a watershed. Although a theoretical concept for this has been published (Heuvelmans et al. 2005) there is still no operational methodology that covers these causal impacts. It is thus the aim of this master thesis to further the representation of causal impacts between land and water use within the framework of LCA.

The following tasks are to be considered:

1. Based on the previous work, make an informed choice of a relevant causal chain
2. Collect data for the relevant pathway from literature
3. Work on developing an effect factor for use in LCIA (applicable for a chosen, relevant world region)
4. Work on developing a fate factor for use in LCIA
5. Make a first attempt at applying fate and effect factor in a case study
6. Discuss the results and uncertainties

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14. January 2015

Olav Bolland
Department Head

F. Verones
Francesca Verones
Academic Supervisor

Preface

I would like to thank my supervisor Francesca Verones for good guidance and support in the process of writing this master thesis. I would also like to thank my family and friends.

NTNU, Trondheim, 11.06.2015, *Martin Moxnes.*

Summary in Norwegian

I denne oppgaven blir årsakssammenhengen mellom avskoging og økt flomfare vurdert for å utvide og forbedre Life Cycle Impact Assessment (LCIA) metodologien. Inntil nylig har Impact kategoriene Water Use og Land Use vært behandlet hver for seg selv om de i realiteten påvirker hverandre. Heulvelmans et al. (2005) laget et rammeverk for årsakssammenhenger mellom Land Use og vannbalansen, men deres arbeid forble teoretisk og operative Characterization Factors ble ikke laget. Denne oppgaven fokuserer på hvordan avskoging fører til økt avrenning av overflate vann gjennom redusert evapotranspirasjon. Dette fører videre til økt flom og skader på mennesker (Damage to Human Health). Denne oppgaven presenterer operative Fate Factors, Effect Factors og Chararacterization Factors for å kvantifisere effektene av avskoging på økt flom og dermed økte skader på mennesker. Damage to Human Health er målt i faktoren ”disability-adjusted life years” (DALY). De beregnede Chararaterization Factors blir tilslutt anvendt i en case studie for Pakistan og Mosambik. Resultatene for Pakistan og Mosambik ble henholdsvis 1.39E-08 DALY/m2 og 5.46E-10 DALY/m^2. Resultatene viser at årsakssammenhengen mellom avskoging og flom er viktig ved betydelig avskoging i sårbare områder.

Abstract

In this thesis the causal chains between deforestation and increased flood impacts are assessed for expanding the life cycle impact assessment (LCIA) methodology. Until recently the impact categories water use and land use have been treated separately, even though they are closely interrelated in reality. Heuvelmans et al. (2005) established a framework for the causal chains between land use and the water balance, but the work stayed theoretical and operational characterization factors did not come out of their approach. The focus of this paper is on deforestation causing increased surface runoff through decreased evapotranspiration. This leads to increased flood impacts on human health. This thesis presents operational fate factors, effect factors and characterization factors for quantifying the impacts from deforestation through floods and increased damage on human health. Human health damage is measured in "disability-adjusted life years" (DALY). The proposed characterization factors are applied in a case study for Pakistan and Mozambique. The results for Pakistan and Mozambique were 1.39E-08 DALY/m2 and 5.46E-10 DALY/m^2 respectively. This result shows that the causal chain is important for substantial deforestations in vulnerable areas.

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1 Introduction

There is an increasing realization that human activity can have a negative impact on the environment, ecosystems, human living conditions and human health. The LCA methodology was developed to capture and measure environmental impacts and is a useful tool for policymaking when planning new industrial, agricultural or other human activities.

In recent years the development of methodologies, especially for assessing impacts from land and water use on ecosystems and human health, has made much progress. However, land and water use are treated as two completely separated impact categories, even though they are closely interrelated in reality. Neglecting the causal chains between impact categories leads to biased results of life cycle impact assessments (LCIA) and to inferior decisions regarding human activities. Deforestation exemplifies the importance of taking interactions between water and land use into account. Deforestation does not only lead to an impact in terms of land use, but also has implications for the microclimate and hydrological cycle (Heuvelmans et al. 2005). Evapotranspiration from trees will be reduced and less water consumed and retained in the soil system around the trees. This can lead to increased runoff, subsequently enabling erosion and ultimately leading to reduced water retention capacity of the soil. Also, this increased runoff potentially leads to higher and faster peak flows in a watershed, which can cause floods.

Another example of the importance of causal links between water and land use is drought, where water depletion caused by human activities affects nearby lakes, rivers and groundwater, which then affects the water availability for the surrounding ecosystem (Pfister et al. 2009, Pfister et al. 2011, Verones et al. 2013a, Verones et al. 2013b). These are some examples of the incompleteness of LCIA methodologies today. In this thesis, I focus on the link between deforestation and increased impacts from flood.

The thesis is organized as follows. First the LCA methodology is described focusing on impact assessment (Chapter 2.1). Then the development of the impact categories land use and water use are described (Chapter 2.2). The work of Heuvelmans et al. (2005) is presented and reviewed (Chapter 2.3). The importance of the central causal link between deforestation and flood, and why it is focused on is discussed (Chapter 2.4). After that relevant data on the link between deforestation and flood is presented together with the most important factors and variables affecting the causal link. A Fate Factor (FF) is presented for quantifying the increase in flood size caused by an increase in deforestation (Chapter 2.5). An Effect Factor (EF) is presented for quantifying the increased impacts on human health from an increase in floods (Chapter 2.6) and a characterization factor (CF) is calculated by combining the Effect Factor and the Fate Factor (Chapter 2.7). Thus, the characterization factor quantifies the changes in impacts on human health due to the effects of deforestation on the water balance. Then the CF is applied for case studies in Pakistan and Mozambique (Chapter 3). Both countries are vulnerable to floods and have been exposed to substantial deforestation. Finally the results of the case studies for the EF, FF and CF are presented, and discussed with focus on importance, quantities, sensitivity, operability and uncertainties (Chapter 4).

2 Materials and methods

In this chapter the procedure for calculating operational Characterization Factors for the causal chain is described. First the LCA and LCIA methodology is described (Chapter 2.1). Then the development of the impact categories land use and water use are described (Chapter 2.2) The work of Heuvelmans et al. (2005) is reviewed with focus on the link between deforestation and flood (Chapter 2.3). Then the causal link is discussed in detail (chapter 2.4) and the FF, EF and CF is developed and described (Chapter 2.5-2.7).

2.1 LCA

Life cycle assessment (LCA) is a methodology for assessing the potential environmental impacts associated with a product or service (Hari Srinivas, n.d.). In ReCiPe (2008) LCA is presented as follows: "The first Life Cycle Assessment (LCA) dates from the 1990s, when the first product studies were made. An LCA is based on a systematic examination of the environmental impacts of products/activities with the aim of revealing the environmental dimension of sustainability". LCA is used to assess and compare environmental impacts from different functional units, which can be different production methods or different alternatives of the same production method (ReCiPe, 2008). In this thesis, the focus is on life cycle impact assessment (LCIA), which is the part of an LCA that calculates and distributes the environmental impacts on different impact categories. The impact categories that I focus on in this paper are water use and land use and the causal chains between them.

The impact assessments of the LCA methodology is based on the impact categories described in ReCipe (2008). This publication quantifies impacts on a midpoint level and endpoint level. Examples of midpoint categories that are relevant for this thesis are; agricultural land occupation, urban land occupation, natural land transformation and water depletion. Examples of endpoint categories are; damage to ecosystem diversity, damage to human health and damage to resource availability (ReCiPe 2008).

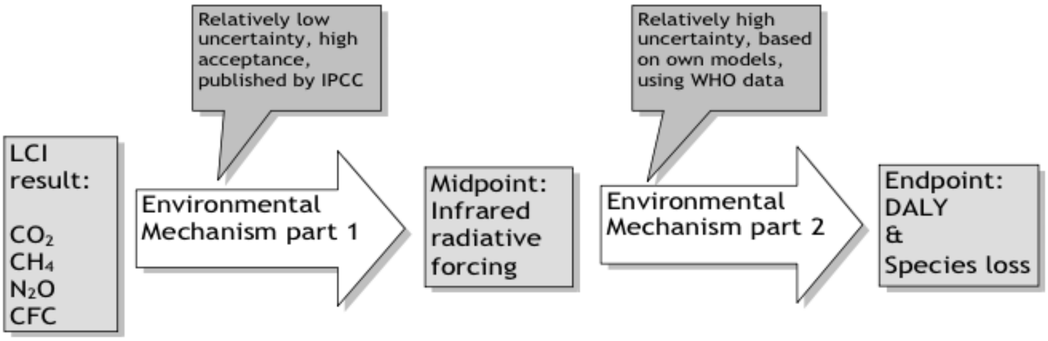


Figure 1 The steps of developing a Characterization Factor (ReCiPe, 2008).

In figure 1 from ReCiPe (2008) the steps for calculating a characterization factor is illustrated through a midpoint-endpoint model. This example is for climate change, but the same procedure applies for the impact pathway by which deforestation causes floods. In our case we get a life cycle inventory (LCI) result in square meters (or kg) of deforested area caused by the functional unit. This leads to an increase in floods at the midpoint due to the environmental mechanism of increased surface runoff. This path is calculated by the fate factor (FF). At the endpoint human health is damaged by the increase in floods, calculated by the effect factor (EF). The total impact pathway from LCI result to the endpoint is calculated by the characterization factor (CF) by multiplying the FF and EF. The path from functional unit to endpoint is described in more detail later.

For calculating the impacts from flood at the endpoint level, the impacts on humans are the most relevant. For assessing damage to human health the concept of “disability-adjusted life years” (DALY) is applied in LCA. DALY is commonly used to assess life years lost and life years lived disabled from diseases, and is derived from human health statistics provided by the world health organization (WHO). DALY is defined by WHO as: ”One DALY can be thought of as one lost year of "healthy" life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability.” (WHO, 2015a).

$$DALY = YLL + YLD \qquad (1)$$

DALY is the sum of years of life lost due to premature mortality (YLL) and years of life disabled (YLD) for people living with a health condition (Equation 1) (WHO, 2015a). In the WHO statistics DALYs are presented for a range of different diseases and injures. Damage to human health due to flood is included in the category “injuries” in the subcategory “exposure to forces of nature”. (WHO, 2015b). Globally, exposure to forces of nature caused 305000 DALY in 2012 and 99000 DALY in 2000. Exposure to forces of nature also includes other natural disasters, for example earthquakes, avalanches, landslides, volcanic eruptions etc. and the numbers should therefore not be used directly for flood alone.

The subcategory “drowning” under the category “injuries” can also be related to flood damage. The majority of drowning in this category is not flood related, but a small part is. “Drowning accounts for 75% of deaths in flood disasters. Flood disasters are becoming more frequent and this trend is expected to continue. Drowning risks increase with floods particularly in low- and middle-income countries where people live in flood prone areas and the ability to warn, evacuate, or protect communities from floods is weak or only just developing.” (WHO, 2015c).

2.2 Impact assessment of water use and land use today

Land use and water use have traditionally been treated separately in LCA even though there are important causal links between them. This section describes how the impact categories water use (water depletion) and land use are measured in ReCiPe (2008) and how they have been updated through new papers and improved for the ReCiPe update (2014). There has been a development of impact categories towards more detailed and improved impact assessments. Describing how land use and water use have been treated as separate impact categories until recently is useful for indicating the importance of studying the causal links between them.

Water use

In ReCiPe (2008) water use was only treated as an abiotic resource that was used as an input for production. The impact category is called freshwater depletion and is simply used to express the total amount of water used. It is only a midpoint indicator as no models at the time were able to express the damage on the endpoint level. A midpoint indicator that only says how much water is used (m^3/year) is not sufficient since ecosystems and human health will be affected in different ways dependent on spatial variability. Water depletion in a dry area will lead to more damage on the endpoint level than similar water depletion in a humid area. ReCiPe (2008) neglects the impacts from water depletion on ecosystems and human health.

Water in life cycle assessment and the impact water depletion has on different ecosystems has been focused on in a number of recent papers and at the 50th Swiss Discussion Forum in 2012 (Tendall et al. 2013). The impact surface- and groundwater depletion has on important international wetlands is described in the paper *Effects of Consumptive Water use on Biodiversity in Wetlands of International Importance* by Verones et al. (2013a). They derive effect factors for quantifying the number of global species-equivalents lost per m^2 of wetland area loss. This approach takes water use from the midpoint category water depletion as stated in ReCiPe (2008) further on to the endpoint category; in this case focusing on ecosystem damage. As the impacts of water use are spatially variable, Verones et al. (2013a) derived effect factors for 1184 different wetlands. In an example involving rose production, the impacts of water use on wetland ecosystems were 67 times larger in Kenya then in the Netherlands due to larger species richness and species vulnerability in Kenya (Verones et al. 2013a).

Hanafiah et al. (2011) focused on the impact water consumption has on fresh water fish species. They used the results to compare the impacts on freshwater fish from water consumption with the impacts from global warming. Spatial variability is a concern and Hanafiah et al. states that; “regionalized inventory data of water consumption are required to apply the new characterization factors in practice” (Hanafiah et al. 2011).

Pfister et al. (2009) assessed environmental impacts of freshwater consumption in LCA on both human health and ecosystem quality, along with resource depletion. In their paper *Assessing the Environmental Impacts of Freshwater Consumption in LCA,* the importance of considering water consumption in water intensive products is assessed. They found that water consumption in water-intensive products such as agricultural products is crucial to take into account in LCIA (Life Cycle Impact Assessment). The importance of regionalized assessments is also emphasized as water use varies greatly as a function of location (Pfister et al. 2009).

In the ReCiPe update (2014), a way to deal with the missing link from midpoint to endpoint for water depletion in ReCiPe (2008) is suggested. The endpoint impacts on human health, terrestrial ecosystems and aquatic ecosystems from water depletion are discussed and calculated. Figure 2 shows the cause-and-effect chain that starts with water consumption (midpoint) and ends with damage to human health based on Pfister et al. (2009), and disappeared terrestrial and freshwater fish species based on Hanafiah et al. (2011).

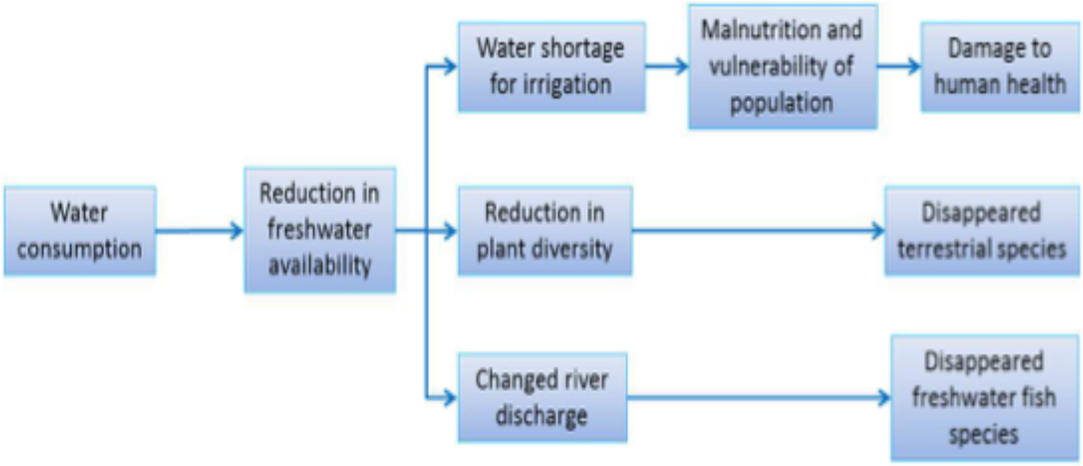


Figure 2 Cause-and-effect chain of water depletion. (ReCiPe update, 2014).

Land use

In ReCiPe (2008) land use is defined as an impact category that reflects the damage to ecosystems due to the effects of occupation and transformation of land. Land use concentrates on two mechanisms:

1. Occupation of a certain area of land during a certain time
2. Transformation of a certain area of land.

These two mechanisms are often combined; occupation typically follows a transformation. The unit of the occupation LCI parameter is m^2*yr. This means that for example the production of a chair will cause a land use impact through the chair factory when it uses a certain amount of square meters for a certain amount of years. Potential Disappeared Fraction (PDF) of species is the endpoint indicator for land occupation and PDF multiplied by restoration time and species density (SD) the endpoint indicator for land transformation. To calculate the impacts from land use, a reference system compares the used land to the same land with no human influence (ReCiPe, 2008). As not all types of land occupation or transformation will have the same effect on the local biodiversity, the type of land use in each case should be indicated. If it affects other impact categories, such as water use, as this paper suggests, this is also of importance.

In the paper: *Land use in Life Cycle Assessment: Global Characterization Factors Based on Regional and Global Potential Species Extinction* by Baan et al (2013), an approach to derive globally applicable CFs of land use is presented. A species-extinction model is used. This approach for assessing impacts of land use in LCA is more complete than previous methods. It provides global CFs for occupation, transformation and permanent impacts, which give decision-makers information on effects of land use, land use changes and the risk of irreversible damage. Baan et al. also criticize the LCA's unit potentially disappeared fraction of species (PDF) for conflating local, regional and global losses. PDF results in a misleading aggregation of impacts on biodiversity of different impact pathways (e.g. land use) modeled at different spatial scales.

In Land stress LC-Impact (2014) it is recognized that human-modified habitats also play an important role in biodiversity conservation and some species can even benefit from human intervention. While some species are highly sensitive to habitat loss and only occur in native habitats, some species show some degree of tolerance to human-modified habitats. Figure 2 (next page) illustrates how land transformation and occupation leads to habitat disturbance, biodiversity loss and ecosystem quality damage.

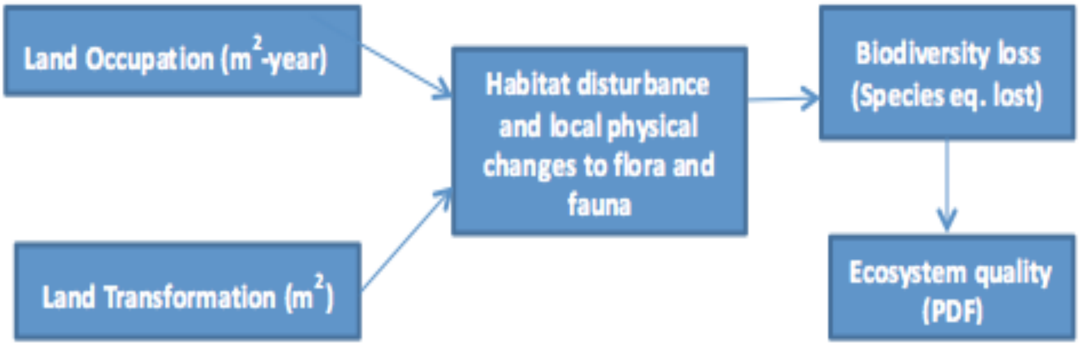


Figure 3 Cause-effect chain describing how land use causes habitat disturbance, which can lead to species extinction and reduced ecosystem quality (Land stress LC-Impact, 2014).

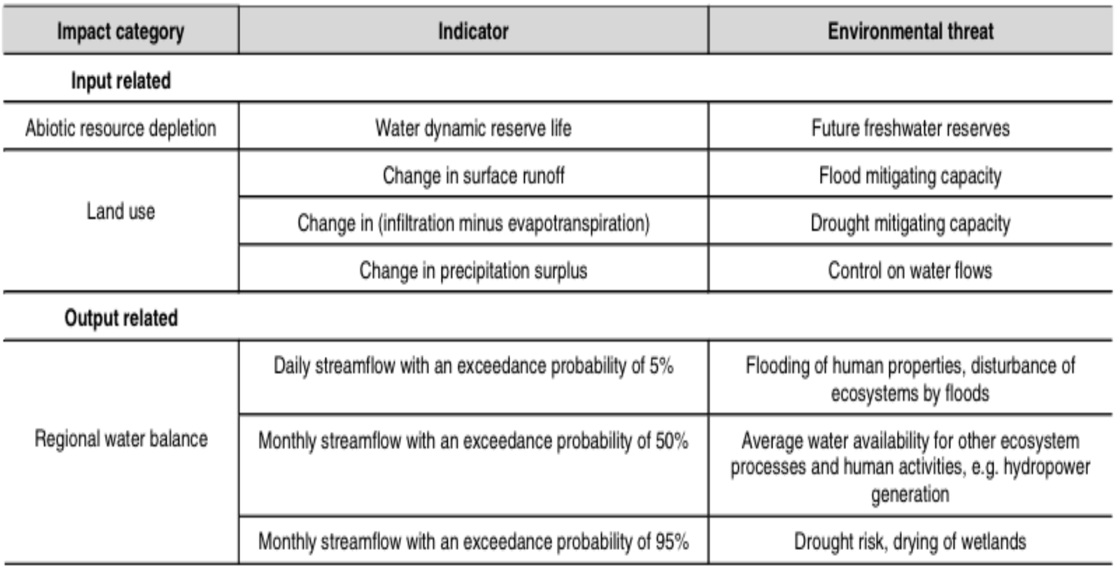
2.3 Review of Heuvelmans et al. (2005)

In this section the findings from Heuvelmans et al. (2005) are summarized. Heuvelmans et al. examined different causal chains between land use and the water balance in order to improve and expand the LCIA methodology. This summary emphasizes the impacts found on flood risk.

Heuvelmans et al. looked at the connection between water flows and land use in the paper *Extending the Life Cycle Methodology to Cover Impacts of Land Use Systems on the Water Balance* from 2005. They found that the impact categories applied in LCA at the time were incomplete when it came to sectors that entail agricultural or silvicultural production systems (food, wood, fiber). Therefore they explored the potential benefits and difficulties of a renewed impact assessment implementing the effects from land use on the water balance.

Heuvelmans et al. divide the causal chains between water and land use into two categories: Input related impacts and output related impacts. Input related impacts contain the two impact categories “Abiotic resource depletion” and “Land use” while output related impacts contain the impact category “Regional water balance”. While the input related impact categories already existed the output related impact category was new and was suggested by Heuvelmans et al. The improved and new impact categories suggested by Heuvelmans et al. can be seen in table 1 (next page) and will be explained and discussed in the next sections.

Table 1: Scheme of an LCIA methodology for assessing impacts on water quantity (Heuvelmans et al. 2005).



Impact category	Indicator	Environmental threat
Input related		
Abiotic resource depletion	Water dynamic reserve life	Future freshwater reserves
Land use	Change in surface runoff	Flood mitigating capacity
	Change in (infiltration minus evapotranspiration)	Drought mitigating capacity
	Change in precipitation surplus	Control on water flows
Output related		
Regional water balance	Daily streamflow with an exceedance probability of 5%	Flooding of human properties, disturbance of ecosystems by floods
	Monthly streamflow with an exceedance probability of 50%	Average water availability for other ecosystem processes and human activities, e.g. hydropower generation
	Monthly streamflow with an exceedance probability of 95%	Drought risk, drying of wetlands

Input related impacts

The indicators suggested by Heuvelmans et al. for assessing the input related impacts from land use on the water balance are listed in Table 1. Land use affects the water balance in two ways, by consuming a certain amount of water and by controlling how excess water runs off. Control of water flows is quantified with the indicator "change in precipitation surplus", which equals precipitation minus evapotranspiration. The part of the excess water that does not infiltrate in the soil or percolates to groundwater forms surface runoff. The indicator "change in surface runoff" is linked to flood risk.

Output related impacts

Heuvelmans et al. focus on three different output related impacts in how land use affects the water balance. These impacts are part of Heuvelmans et al.'s new output related impact category "Regional water balance", which is meant to fill a gap in the existing life cycle impact assessment. The difference between the impact category "Regional water balance" and the impacts on water described under the input related impact category "land use" is that "Regional water balance" calculates and assesses indicators while activities go on. This is a more "day to day and month to month" approach than the land use category, which focuses on the changed hydrological behavior after one crop rotation of used or occupied land.

The three output-related impacts under the impact category "Regional water balance" are shown in Table 2. Heuvelmans et al. have made indicators for how the changes in water outputs from a land use area affect flooding, average water availability downstream, and drought risk. The indicators in the "Regional water balance" impact category are based on daily (flood risk) and monthly (average water availability and drought risk) stream flows. They have been calculated from a theoretical example for the Maarkebeek catchment with data collected by the Flemish environmental administration (AMINAL). Heuvelmans et al. sort the stream flow observations from low to high flow values, rescale the data to the appropriate time step, and calculate the 50th quantile for calculating average water availability, the 5th quantile for calculating drought risk and the 95th quantile for calculating flood risk (Heuvelmans et al. 2005).

Equations 2 and 3 from Heuvelmans et al. (below), indicate how land use impacts the water flows. The land use area (system under study) is compared to the potential natural vegetation in that area (reference system). Equation 2 is applied for water availability and drought risk and a positive score indicates reduced water availability and increased drought risk. Equation 3 is applied for flood risk and a positive score indicates increased flood risk. To calculate the regional water balance indicators, stream flow records must be available. Ecosystems and human health are the areas of protection for the regional water balance impact category (Heuvelmans et al. 2005).

$$Ind_B = \frac{Ind_{B_{ref}} - Ind_{B_{act}}}{Ind_{B_{ref}}} \qquad (2)$$

Where:

Ind_B: normalised indicator of average downstream water availability and drought risk

$Ind_{B_{ref}}$: (non-normalised) indicator for the reference system

$Ind_{B_{act}}$: (non-normalised) indicator for the system under study

$$Ind_C = \frac{Ind_{C_{act}} - Ind_{C_{ref}}}{Ind_{C_{ref}}} \qquad (3)$$

Where:

Ind_C: normalised indicator of flood risk

$Ind_{C_{ref}}$: (non-normalised) indicator for the reference system

$Ind_{C_{act}}$: (non-normalised) indicator for the system under study

Heuvelmans et al. state that the temporal variations in water flows should be taken into account when calculating impacts. Variation is of high importance for the magnitude of the impacts. Especially for flood risk the temporal variability is important. The average precipitation over a watershed in a year does not necessarily say much about the flood risk. Therefore the peak flows should be the indicator for flood risk. As Heuvelmans et al. state: “If all water is emitted at once, the flood risk will be higher than when water is released slowly”. Temporal variability in water flows also applies for drought impacts, if a plant needs water evenly over a year it can still die in a year with high average precipitation if the water flows are unevenly distributed. Temporal variability is therefore taken into account when calculating the indicators for regional water balance as explained in the output related impacts section above.

Feasibility of Heuvelmans et al.

A challenge with Heuvelmans et al. is that streamflow data are not always accessible, which questions the feasibility of the method on a global scale. Many hydrological models exist though, for example the SWAT model (Soil and Water Assessment Tool), which can estimate streamflows from data on climate, topography, soil properties, land use and crop properties (Gassman et al. 2007). Hydrological models such as SWAT can give data for almost every case study, but the accuracy is very dependent on the quality and representativeness of the input data.

SWAT models were applied for 25 different catchments in the Flemish part of the Scheldt river basin with site-specific parameters and with default settings. Calibration of the parameters considerably increased the performance of the model in most of the catchments, which implies that default settings do not suite the Flemish catchments (Heuvelmans et al. 2005). This demonstrates that using one worldwide applicable model with a given parameter set is not recommended. A regionalization of parameter estimates is therefore desired. Heuvelmans et al. conclude that regionalization has the potential to improve the quality of studies simulating the impact of alternative land use scenarios on catchment hydrology. The main drawback for Heuvelmans et al.´s proposed method for increasing the credibility of the impact assessment is the increased data requirements and adaption of data for different locations. They also need more detailed numerical models on a local level.

2.4 The causal chain between deforestation and flood

In an earlier project work with the title: *Causal chains between water and land use in Life Cycle Assessment* (Moxnes 2014), four links between water and land use were presented and discussed. The causal links identified and described in the project work were; deforestation, afforestation, water depletion causing ecosystem damage in water-limited environments and urban land use. In this chapter the link between deforestation and increased flood impacts is described further.

While Heuvelmans et al. were the first to study the causal chains between land use and the water balance for LCIA the work stayed theoretical and did not get to the point of calculating operational characterization factors (CF) for the causal chains between water and land use on a global level. This chapter explains the link between deforestation and floods further, and presents the theory used for constructing characterization factors. Deforestation worldwide annually averaged approximately 14.6 million hectares (ha) between 1990 and 2000 (Sweeney et al. 2003).

The link between deforestation and increased flood risk has been acknowledged for a long time. It was already studied in the paper *Effects of forest cutting and herbicide treatment on nutrient budgets in the hubbard brook watershed-ecosystem* by Likens et al. (1969). After all vegetation in Watershed 2 of the Hubbard brook experimental forest was cut in 1965 and vegetation regrowth was inhibited for two years, they found that the annual streamflow increased 33cm or 39% the first year and 27cm or 28% the second year. These numbers are relative to expected streamflow before deforestation (Likens et al, 1969).

In the *paper Global evidence that deforestation amplifies flood risk and severity in the developing world* by Bradshaw et al. (2007) they show that flood frequency is negatively correlated with the amount of remaining natural forest and positively correlated with natural forest area loss. Bradshaw et al. (2007) used data collected from 1990 to 2000 from 56 developing countries. The importance of investigating possible reasons for increased flood risk is shown by the fact that 100 000 people were killed and 320 million people were displaced by floods during the decade investigated by Bradshaw et al. (2007). Even though the number of deaths from flood are relatively small compared to deaths by diseases or other injuries it is still important. The number of displaced people due to floods is very important as it destroys livelihoods and therefore creates more pressure elsewhere.

Bradshaw et al. (2007) were the first to predict flood frequency and severity over broader spatial scales; this approach is very useful for developing an impact assessment that applies for LCIA. Bradshaw et al. (2007) tested two general, but linked hypotheses: "…(i) that flooding frequency (risk) increases as natural forest cover decreases and (ii) that severity (measured as total flood duration, the number of people killed or displaced, and infrastructure damage) associated with floods is higher when natural forest cover is lower."

Some of the findings by Bradshaw et al. (2007) are shown in figure 4 and 5 (next page). They are most useful when choosing and quantifying the input parameters for the FF and EF. Figure 5 shows scatter plots of flood frequencies versus size of area studied (a), increased average annual precipitation (b), increased average slope (c) and increased degraded area (d). The scatter plots are consistent to expected causalities, but does not necessarily prove them.

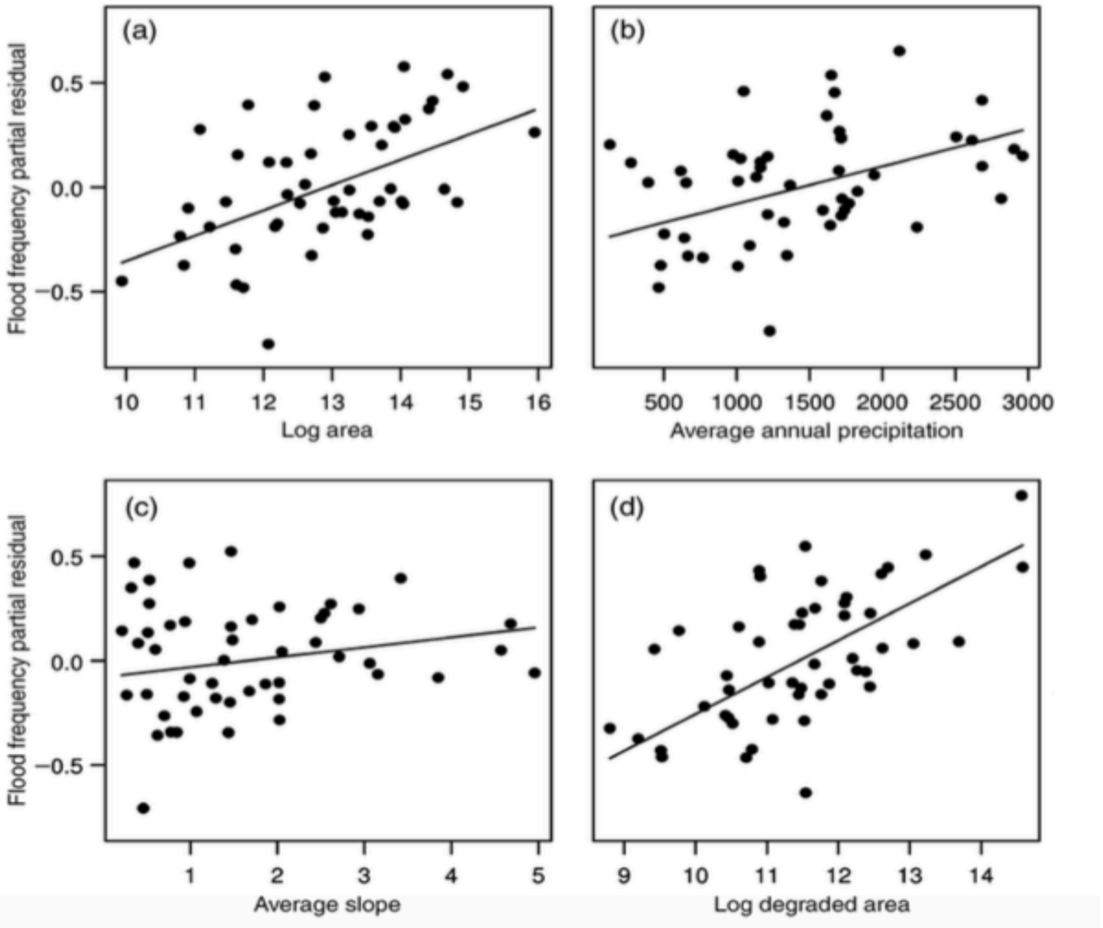


Figure 4 Scatter plots of flood frequencies versus size of area studied (a), average annual precipitation (b), average slope (c) and degraded area (d) (Bradshaw et al, 2007).

Figure 5 shows the effect loss of natural forest has on flood frequency and duration.

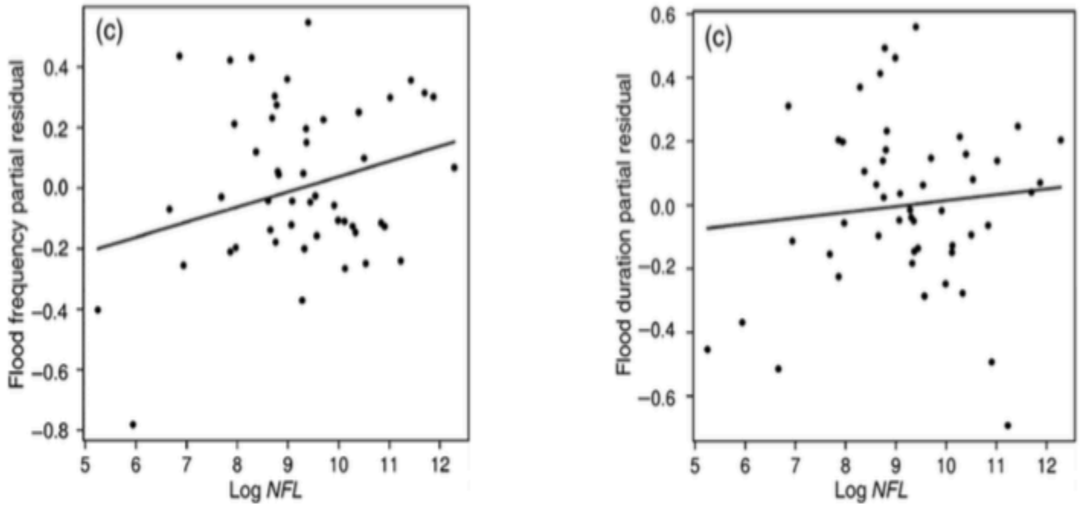


Figure 5 Data indicating effects of Natural Forest Loss (NFL) on flood frequency and duration (Bradshaw et al. 2007)

While Heuvelmans et al. (2005) and the project work (Moxnes, 2014) presented several paths between land use and the water balance this thesis focuses on the change in floods due to deforestation. Figure 6 (below) illustrates the complexity of the link between deforestation and floods.

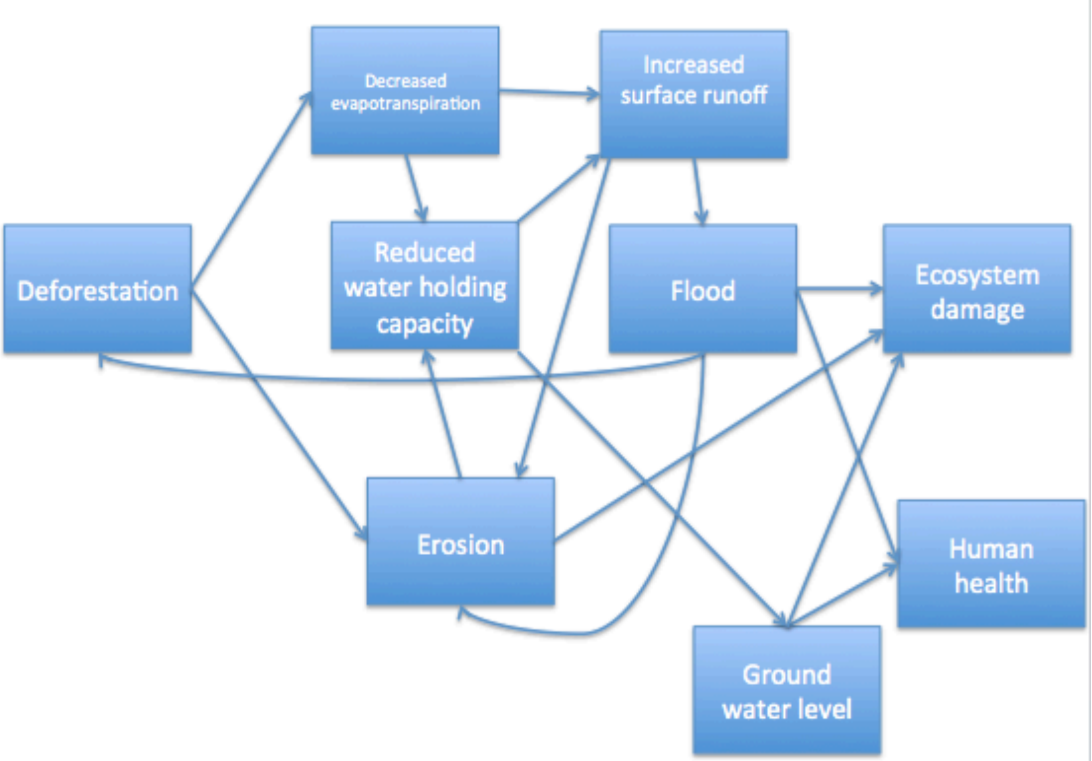


Figure 6 Likely causal chains between deforestation and flood.

According to Heuvelmans et al. (2005) deforestation lead to floods through decreased evapotranspiration, increased surface runoff and through increased erosion. However, there are several other causal chains between deforestation and flood risk that can be relevant to form a more accurate impact assessment. Figure 6 visualizes various paths from deforestation to impacts on human health and ecosystems at the endpoint level.

First deforestation leads to erosion for several reasons. Forests form a complex network of roots that is effective in holding the soil together. A protective layer of humus and litter usually covers the surface of the forest soils (preventing splash erosion from heavy rainfall), and forests have less surface runoff of water to streams (stream erosion) (Sands, Roger 2005). ReCiPe (2008) acknowledges that erosion is one of the important missing aspects at the midpoint level. Both erosion and decreased evapotranspiration leads to a reduction in the deforested areas water holding capacity. When the deforested areas water holding capacity is reached, the excess water will form surface runoff, which can lead to flood. Over time, decreased water holding capacity can lead to decreased groundwater levels, as less water will percolate into the ground.

Figure 6 contains reinforcing loops that can increase the impacts from deforestation on the water balance. The arrows from flood back to deforestation and erosion proposes that when an area is exposed to floods, mainly caused by deforestation, more trees can fall down and more soil can erode. The floods cause stream erosion where soil is dragged along with the flooding water. Trees can fall down directly by flooding or indirectly by earth eroding underneath them. It is a reinforcing loop where floods lead to deforestation and erosion, which again leads to more frequent or bigger floods.

Human health can be damaged directly through flood victims or indirectly through damaged food or water resources. Human health can also be affected indirectly from flood if ecosystems that provide food or other benefits are damaged. When it comes to direct damages to human health the placement of the deforested area relative to densely populated areas should be taken into account. Damage to ecosystems can occur directly from flooding as species both terrestrial and aquatic can be damaged or disappear. Both natural and human influenced ecosystems can be affected. Indirectly, erosion and changes in groundwater level can cause ecosystem damage. "Soil erosion clearly reduces the fertility, productivity and utility of the soil at the site of which it has eroded" (Sands, Roger 2005). Ecosystems can also be damaged directly by deforestation through species extinction.

Deforestation and flood as an example of causal chains between water and land use can thus become very complex and data demanding, and it should therefore be assessed which level of complexity to aim for. For simplicity not all possible links between deforestation and flood risk have been included in figure 4, only the links considered most relevant have been focused on. The Characterization Factors to be developed later will be even more simplified for operability.

"Moreover, the strong relationship between evapotranspiration rates and rainfall (Zhang et al., 2001) will contribute further site-specific complexity to estimates of flooding risk." Bradshaw et al. (2007, page 2390). Bradshaw et al. (2007) emphasizes that including rainfall and evapotranspiration rates is important for a more detailed and regionalized study. Therefore, the importance of the change in evaporation rates after deforestation is presented in the next section and included in the Fate Factor.

2.5 Fate Factor

The fate factor calculates the change in water yield due to deforestation. It is developed by gathering information through literature. For the development of the fate factor the most general, important and feasible variables were chosen, for example precipitation, evaporation and slope. By the term general is meant variables that can be applied on a large scale (globally), some of the variables found in only a small sample of the literature study are only relevant on a local scale. The contributions of the chosen and rejected variables are discussed further in chapter 3.

Table 2 List of input parameters for the proposed fate factor:

Input parameters	***Unit***
Potential Evapotranspiration (PET)	mm/yr
Plant-available water coefficient (w)	-
Actual Evapotranspiration (AET)	mm/yr
Precipitation	mm/yr
Surface runoff (water yield)	mm/yr
Area rained on	m^2
Slope	degrees

Change in water yield (surface runoff)

The paper *Regional annual water yield from forest lands and its response to potential deforestation across the southeastern united states* by Sun et al. (2004) describes how precipitation minus evapotranspiration equals water yield (equation 4, below). “Regional water yield at a meso-scale can be estimated as the difference between precipitation input and evapotranspiration output. Forest water yield from the southeastern US varies greatly both in space and time. Because of the hot climate and high evapotranspiration, less than half of the annual precipitation that falls on forest lands is available for stream flow in this water rich region. Water yield is highest in the mountainous regions that receive the highest precipitation and have the lowest air temperature, and the lowest in the coastal regions that are dominated by wetlands receiving moderate rainfall but high evapotranspiration. Water resource management for both floods and droughts demands an accurate estimation of water yield from forests. Projected climate and land use changes further increase the variability of water yield in the region.” (Sun et al. 2004, page 258).

$$Y = P - AET \quad (mm/year) \qquad (4)$$

Equation 4 (Sun et al. 2004) describes how water yield is equal to precipitation (P) minus actual evapotranspiration (AET). This gives a good indication of the surface runoff from a watershed, but it does not take all variables shown in Figure 6 into account. The relationship between evapotranspiration, groundwater recharge and surface runoff is illustrated in Figure 7 (next page).

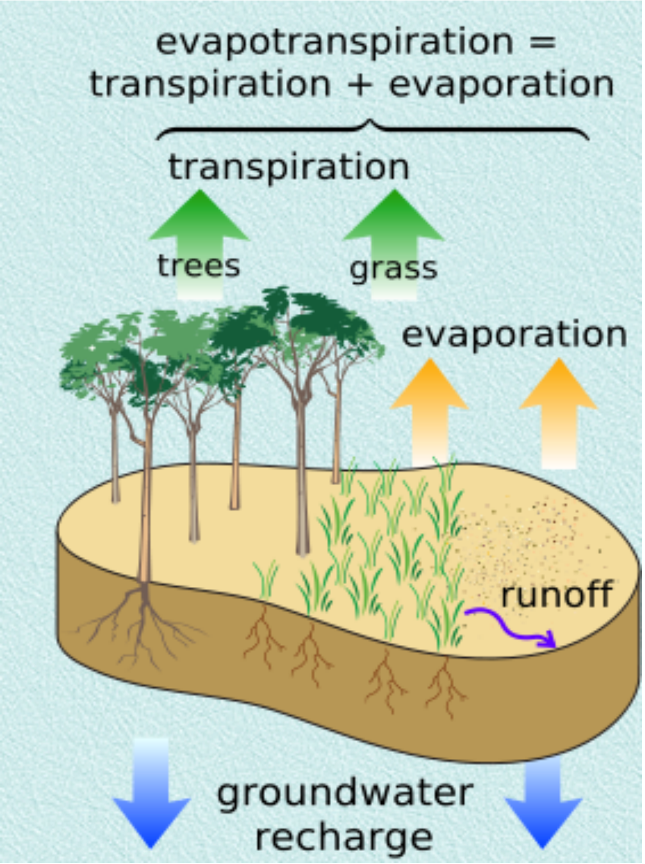


Figure 7 Evapotranspiration, groundwater recharge and surface runoff (K3JAE, 2015)

The advantage of Sun et al.`s approach is that all the needed input data is available on a global level. Streamflow data is not necessary. "When using the Zhang model (Equation 5, described below) it gives a good predictive tool for estimating the change in water yield between grass and forested catchment…" (Brown et al. 2005).

"It is now well established that forested catchments have higher evapotranspiration than grassed catchments. Thus land use management and rehabilitation strategies will have an impact on catchment water balance and hence water yield and groundwater recharge. The key controls on evapotranspiration are rainfall interception, net radiation, advection, turbulent transport, leaf area, and plant-available water capacity. The relative importance of these factors depends on climate, soil, and vegetation conditions. Results from over 250 catchments worldwide show that for a given forest cover, there is a good relationship between long term average evapotranspiration and rainfall." (Zhang et al. 2001, page 701). Zhang et al.`s model is shown in equation 5.

$$AET/P = \frac{1 + w\,\frac{PET}{P}}{1 + w\,\frac{PET}{P} + \frac{P}{PET}} \qquad (5)$$

The ratio of actual evapotranspiration (AET) to precipitation (P) is calculated according to Equation 5 developed by Zhang et al. (2001). The ratio depends on precipitation (P), potential evapotranspiration (PET) and the plant-available water coefficient (w). When w tends towards infinity, the ratio tends towards 1.0. Equation 5 was developed using hydrologic data from over 250 watersheds worldwide across a wide range of climatic zones (Zhang et al. 2001). The potential evapotranspiration is the evapotranspiration that occurs when the ground is completely covered by actively growing vegetation and there is no limitation in the soil moisture (Waterwiki, 2010). PET varies with climate, and data are available globally. The w coefficient is applied to calculate the difference in evapotranspiration for different vegetation types. The default w coefficients were reported as 0.5 for shortgrass and crops and 2.0 for forests (Zhang et al. 2001). Sun et al. (2004) further improved the accuracy of the w coefficient and found that deciduous and conifer trees should have a w coefficient of 2.8 and urban lands a w coefficient of 0.

$$AET = \sum(AET_i \times f_i) \qquad (6)$$

If the watershed under study contains different types of land use (vegetation) the average AET can be calculated by the weighted sum of the AETs of the different land uses (i) were f_i is the percentage of land use i (Equation 6) (Sun et al. 2004).

Actual evapotranspiration after a land transformation ($AET_{transformed}$) is thus different from AET before the land transformation ($AET_{reference}$) due to the change in the w coefficient. For the deforestation case $AET_{transformed}$ is typically agricultural land (w = 0.5) or urban land (w=0) and $AET_{reference}$ is typically forestland (w=2 to 3, dependent on forest species).

Ruprecht & Schofield (1989, page 15) supports the findings of Sun et al. regarding the reason for increased streamflow in general: "The source of the increase in streamflow is the decrease in evapotranspiration caused by replacing native deep-rooted species with agricultural shallow rooted species."

Slope

Steeper slopes of the deforested areas lead to higher flood risks. Bradshaw et al (2007) found a tendency that countries with high average slope had a higher flood frequency than countries with low average slopes. As seen in Figure 5 the average slope of a country influences the flood frequency, but not severely. The average slope of a country can be a misleading variable, as it does not show what the most common slope is (median).

Also floods in steep areas are typically more deadly as they will have higher speeds and are more likely to cause erosion. "The lives were lost mostly in the upper part of the catchment where the river gradient and flow velocities were highest…" (Straatsma et al. 2010).

Precipitation

"Indeed, the principal flood generating factor is rainfall intensity and duration within a catchment's boundary…" (Bradshaw et al. 2007, page 2381).

Precipitation is an important variable since there is a clear link between annual precipitation and flood risk (Figure 5). A high daily precipitation for several days in a row will typically lead to floods. This happened on the west coast of Norway in 2014 where it rained for several days in a row causing a flood. It rained until the ground could now longer absorb the large amount of water. (Rommetveit, A, 2015). In the Fate Factor annual precipitation enters the equation for change in surface runoff. This is a simplified approach compared to Heuvelmans et al. (2005), but it gives an indication of the flood risk relative to precipitation and is easier to estimate, as it does not require streamflow data.

Area rained on

Area rained on is needed to quantify the total precipitation in an area. For the proposed fate factor it is typically one square meter.

Fate Factor (FF)

The fate factor (Equation 7) calculates the effect of deforestation on water yield (multiplied by slope). Equation 8 is a more detailed version of the FF and Equation 9 shows the units of the FF. The equations are explained below.

$$FF = \frac{\delta Y * A_{rained\ on} * S}{A_{deforested}} \qquad (7)$$

$$FF = \frac{\left((\mathrm{P} - AET_{transformed}) - (\mathrm{P} - AET_{reference})\right) * A_{rained\ on} * S}{A_{deforested}} \qquad (8)$$

$$FF = \frac{{m^3}/{(m^2 * yr)} * m^2 * {m}/{m}}{m^2} = \frac{m^3/yr}{m^2} \qquad (9)$$

Above (Equation 4) it is argued that when simplified the streamflow in a watershed is equal to precipitation minus actual evapotranspiration (Sun et al. 2004). Deforestation or afforestation thus leads to a change in the plant-available water coefficient w causing a change in actual evapotranspiration and therefore also a change in water yield (δY). The change in water yield is found by calculating the difference in water yield after land transformation ($Y_{tansformed}$ = P-$AET_{transformed}$) to the water yield before land transformation ($Y_{reference}$ = P-$AET_{reference}$). Precipitation is measured in mm, which can be transformed to liters per square meter. When multiplying the change in water yield in liters (0.001m^3) per m^2 with area rained on in m^2, the change in water yield is obtained in m^3. The total change in water yield is then multiplied with the slope (S). The slope is measured in meters elevated per horizontal meters (used for calculation) or in degrees (is converted to m/m for calcuaitons). A steep slope increases the impact of the flood compared to a slight slope. The change in water yield is per square meter of transformed land and the impact of a change in water yield is spatially dependent. The locations of impact assessments applying the FF can be in the magnitude of catchments, watersheds or countries. In a case where $Y_{transformed} < Y_{reference}$ (afforestation) the output of the FF will be negative.

2.6 Effect factor

The effect factor is calculated by dividing DALY per year for an area (country) with flood size per year for the same area. Thus quantifying the impacts from floods on human health at the endpoint. Flood size is equal to flood distribution multiplied with flood depth. The input parameters for the EF is found in Table 3, and described below.

Table 3 List of input parameters for the proposed effect factor.

Input parameters	***Units***
Flood distribution	m^2
Flood depth	m
DALY	disability adjusted life years

Flood distribution

The size of the area a flood impacts is an important parameter for calculating the potential damage caused. The size of a flood is difficult to quantify, areas affected ranged from 1170 to 78900 km^2 according to Bradshaw et al. (2007). The flood distribution can be one individual flood, or the total area of floods in a country or region in a year.

Flood depth

The depth of a flood varies greatly with location (see chapter 4.3), but the parameter is important for damage assessment and for quantifying floods when multiplied with the flood distribution.

DALY

Disability adjusted life years (DALY) is a parameter that quantifies damage on human health. For the effect factor the DALY categories “drowning” and “exposure to forces of nature” can be used to assess damage from floods. The DALY categories were described in more detail in the earlier section on LCA (Chapter 2.1). Factors such as population density, GNP, health care and location of floods relative to cities will affect the damage from floods. When comparing DALY per year relative to number and sizes of floods per year for a country these factors are taken into account.

Population density is measured for each country in population per km^2. A high amount of people in an area results in higher DALY per m^3 of flood. Since 54% of the global population lives in urban areas (WHO, 2015d) the location of the floods will impact the effect factor. A flood in a city causes more damage to human health than a flood in an uninhabited area.

Since developing countries have fewer resources to protect themselves from floods, living standard (GNP) will affect DALY per m^3 of flood, and good healthcare and treatment of flood victims will also reduce the DALY impact.

Effect factor (EF)

The effect factor presented in equation 10 is calculated by dividing DALY per year for an area (country) with flood size per year for the same area. Thus quantifying the impacts from floods on human health at the endpoint. Flood size is equal to flood distribution multiplied with flood depth. The units are shown in Equation 11.

$$EF = \frac{Disability\ adjusted\ life\ years}{Flood\ distribution * Flood\ depth} \qquad (10)$$

$$EF = \frac{DALY/yr}{(m^2 * m)/yr} = \frac{DALY}{m^3} \qquad (11)$$

2.7 Characterization factor

The characterization factor is calculated by multiplying the fate factor and the effect factor (Equation 12). The unit for the CF thus becomes DALY/(m^2*yr) (Equation 13) When multiplying the CF with the deforested area per functional unit, the total human health damage caused by the increased flood is calculated. Deforested area is measured in m^2 and is the amount of forest transformed into agricultural land, urban land or grassland etc.

$$CF = FF * EF \qquad (12)$$

$$CF = \frac{m^3/yr}{m^2} * \frac{DALY}{m^3} = \frac{DALY}{m^2 * yr} \qquad (13)$$

The size of deforested area per functional unit depends on how much timber in kilograms the functional unit requires or the size of transformed forestland caused by the functional unit. If the functional unit requires timber directly the density of the forest will determine the deforested area (m^2) per kg of applicable timber. If the functional unit requires land transformation for example for agriculture, roads or urban land, the degree of deforestation will depend on the forest cover relative to the total transformed land. This could be measured in leaf area index (LAI, described in Chapter 4?) (Osturk, Copty, Saysel, 2013).

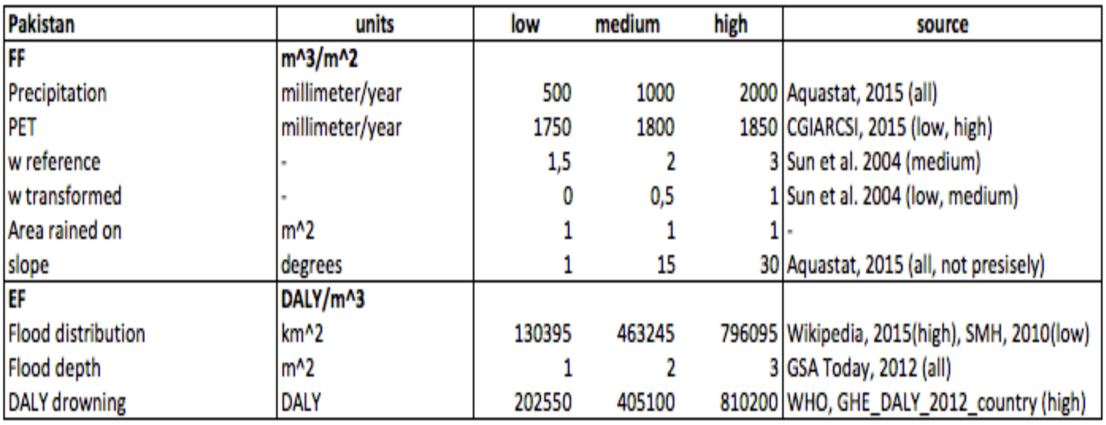
3 Case study

Pakistan and Mozambique were chosen as locations for the case study. These two countries from Asia and Africa respectively have different input parameters for the impact assessment due to different climate, ecology and geography etc. The countries have a history of large flood impacts in common. Having a case study for two different regions is convenient for comparison of the results and uncertainties. All the input parameters are given for low, medium and high estimates, as the input data are uncertain. The input data can also vary with location within the countries. This gives an indication of the sensitivity of the CF. A regular sensitivity analysis is done for the Paksitan case as well (Table 12). Not all input values are gathered from data sources, some are assumed or used for testing the variance in the results (w values and slope).

3.1 Pakistan

Pakistan was chosen for the case study, as it is a country that has been exposed to floods in the past, has a large population and a varying topography. The specific flood used in this case study was along the Indus river basin in 2010, a flood that affected 20 million people (SMH, 2010). The Indus river basin includes steep slopes in the Himalayan Mountains in the north and the dry plains of the Sindh province in the south. The annual precipitation varies from 100-500 mm/year in the lowlands to 2000 mm/year in the mountains (Aquastat, 2011). The DALY category used for Pakistan is “drowning”, as DALY data from WHO are from 2012 and therefore do not include this flood (2010) in “exposure to forces of nature”. “Drowning” (810200 DALY in 2012) is assumed mainly to include not flood related drowning and is therefore set as a “high” value (Table 4). Pakistan is interesting as a case study as it lost 33,2 % of its forest cover between 1990 and 2010, a total of 8400 km^2 (Mongabay, 2009).

Table 4 Input parameters, case study Pakistan.

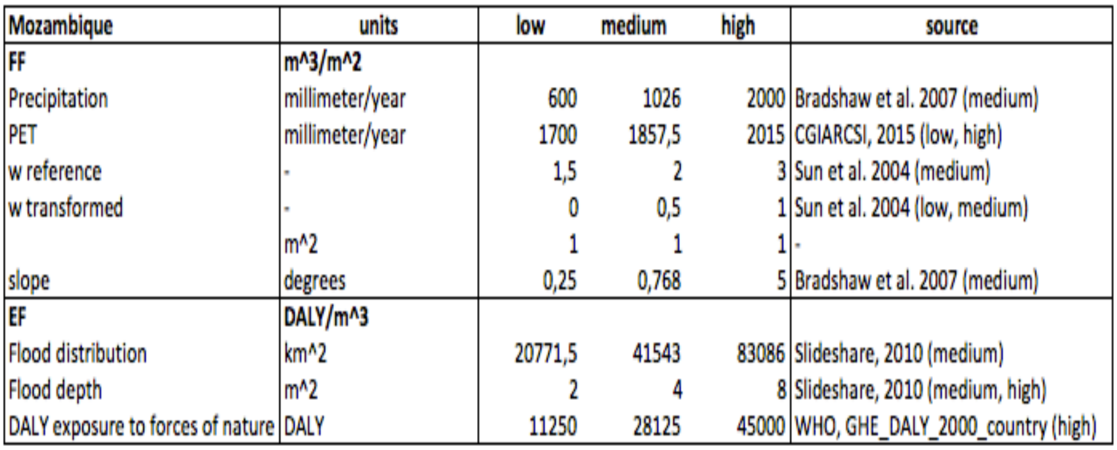


Pakistan	units	low	medium	high	source
FF	**m^3/m^2**				
Precipitation	millimeter/year	500	1000	2000	Aquastat, 2015 (all)
PET	millimeter/year	1750	1800	1850	CGIARCSI, 2015 (low, high)
w reference	-	1,5	2	3	Sun et al. 2004 (medium)
w transformed	-	0	0,5	1	Sun et al. 2004 (low, medium)
Area rained on	m^2	1	1	1	-
slope	degrees	1	15	30	Aquastat, 2015 (all, not presisely)
EF	**DALY/m^3**				
Flood distribution	km^2	130395	463245	796095	Wikipedia, 2015(high), SMH, 2010(low)
Flood depth	m^2	1	2	3	GSA Today, 2012 (all)
DALY drowning	DALY	202550	405100	810200	WHO, GHE_DALY_2012_country (high)

3.2 Mozambique

Mozambique was exposed to a large flood caused by heavy rainfall in 2000. The flood resulted in 800 deaths and 1400 km^2 of arable land was affected (Wikipedia, 2015b). This flood was chosen for the case study because WHO has DALY statistics on exposure to forces of nature from the year of the flood (2000). The flood was followed by the tropical Cyclone “Eline” (Slideshare, 2010), which contributed to the DALY statistics for Mozambique in 2000. Therefore DALY caused by exposure to forces of nature from WHO (45000 DALY) are under “high” in the EF input and not “medium” to correct for this. The “medium” value for precipitation is average precipitation in Mozambique per year. The average slope of Mozambique is used as the “medium” slope (Table 5). Mozambique lost 10 % of its forest cover between 1990 and 2010, a total of 43560 km^2 (Mongabay, 2011). As a response to the flood trees were planted to soak up water before reaching the river (Slideshare, 2010).

Table 5 Input parameters, case study Mozambique.



Mozambique	units	low	medium	high	source
FF	**m^3/m^2**				
Precipitation	millimeter/year	600	1026	2000	Bradshaw et al. 2007 (medium)
PET	millimeter/year	1700	1857,5	2015	CGIARCSI, 2015 (low, high)
w reference	-	1,5	2	3	Sun et al. 2004 (medium)
w transformed	-	0	0,5	1	Sun et al. 2004 (low, medium)
	m^2	1	1	1	-
slope	degrees	0,25	0,768	5	Bradshaw et al. 2007 (medium)
EF	**DALY/m^3**				
Flood distribution	km^2	20771,5	41543	83086	Slideshare, 2010 (medium)
Flood depth	m^2	2	4	8	Slideshare, 2010 (medium, high)
DALY exposure to forces of nature	DALY	11250	28125	45000	WHO, GHE_DALY_2000_country (high)

4 Results and discussion

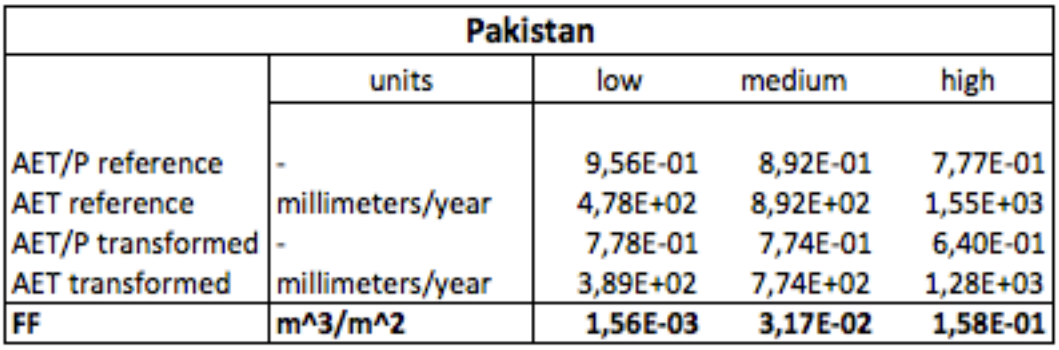
In this chapter the results of the case studies for Pakistan and Mozambique and a sensitivity analysis for the Pakistan case study are presented and discussed. After that uncertainties regarding choice of input parameters, quantification of the input parameters and neglected parameters are discussed.

4.1 Results of the case studies

The results of the case study are presented in Tables 6 to 11. For the fate factor the Pakistan case study has a larger impact on water yield and slope per deforested area then Mozambique for all values (Tables 6 & 7). This can be explained by a higher "low" value for Pakistan on PET and slope, and by a steeper slope for Pakistan on the "medium" and "high" values compared to Mozambique (Tables 4 & 5).

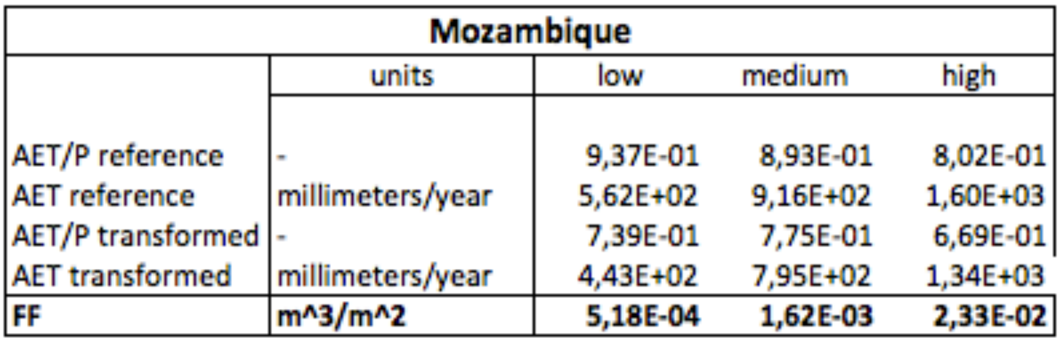
Fate Factor (FF)

Table 6 Fate Factor Pakistan



Pakistan				
	units	low	medium	high
AET/P reference	-	9,56E-01	8,92E-01	7,77E-01
AET reference	millimeters/year	4,78E+02	8,92E+02	1,55E+03
AET/P transformed	-	7,78E-01	7,74E-01	6,40E-01
AET transformed	millimeters/year	3,89E+02	7,74E+02	1,28E+03
FF	**m^3/m^2**	**1,56E-03**	**3,17E-02**	**1,58E-01**

Table 7 Fate Factor Mozambique

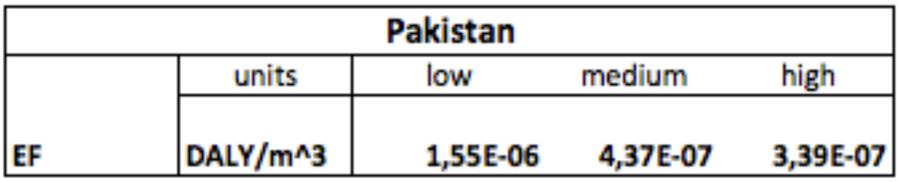


Mozambique				
	units	low	medium	high
AET/P reference	-	9,37E-01	8,93E-01	8,02E-01
AET reference	millimeters/year	5,62E+02	9,16E+02	1,60E+03
AET/P transformed	-	7,39E-01	7,75E-01	6,69E-01
AET transformed	millimeters/year	4,43E+02	7,95E+02	1,34E+03
FF	**m^3/m^2**	**5,18E-04**	**1,62E-03**	**2,33E-02**

Effect factor (EF)

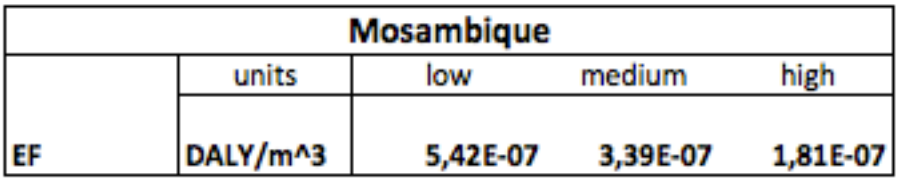
The results of the EF (Table 8 & 9, below) show that Pakistan has the highest EF for all values, but the difference compared to Mozambique is not severe. While Pakistan has an approximately 14 times higher DALY value then Mozambique (medium value, Table 4 & 5) the EF is evened out since Pakistan has a proportionally larger flood size.

Table 8 Effect Factor Pakistan



Pakistan				
	units	low	medium	high
EF	DALY/m^3	1,55E-06	4,37E-07	3,39E-07

Table 9 Effect Factor Mozambique

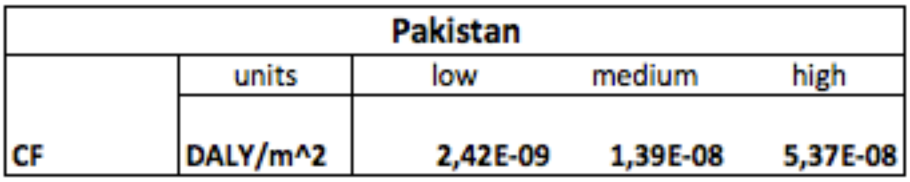


Mosambique				
	units	low	medium	high
EF	DALY/m^3	5,42E-07	3,39E-07	1,81E-07

Characterization Factor (CF)

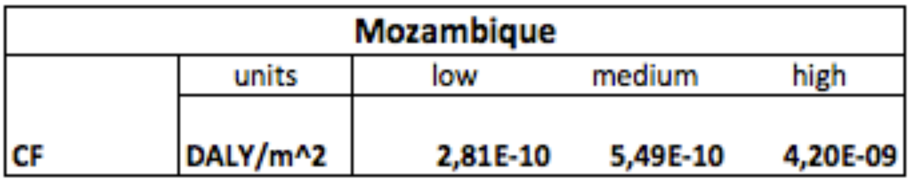
The Characterization factors (Tables 10 & 11, below) are found by multiplying the FF and EF. Since Pakistan had the highest impacts on both the FF and EF compared to Mozambique, the CF is also highest accordingly. For the “medium” values the Pakistan CF is 25 times higher than the CF for Mozambique.

Table 10 Characterization Factor Pakistan



Pakistan				
	units	low	medium	high
CF	DALY/m^2	2,42E-09	1,39E-08	5,37E-08

Table 11 Characterization Factor Mozambique



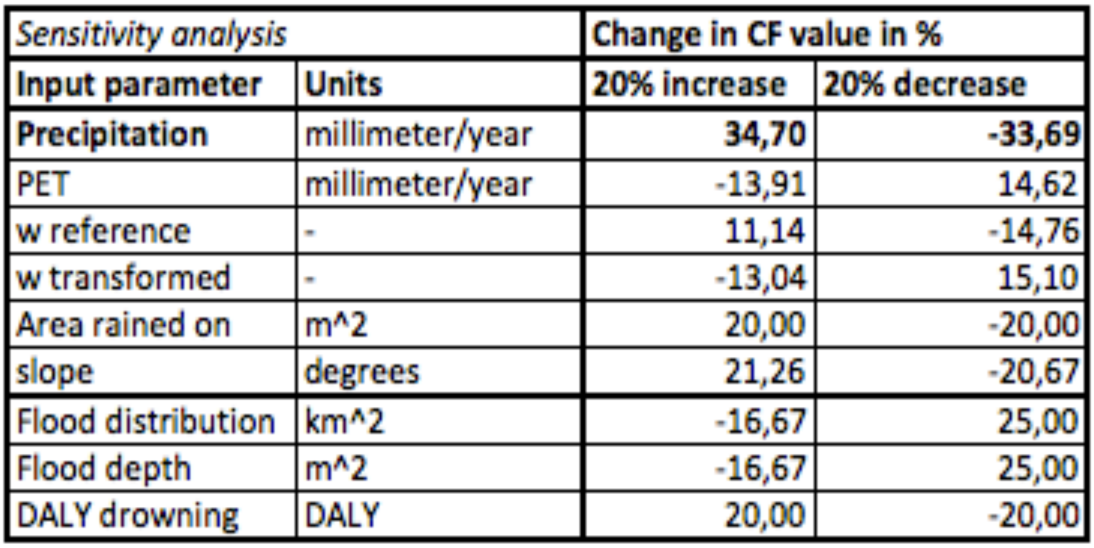
Mozambique				
	units	low	medium	high
CF	DALY/m^2	2,81E-10	5,49E-10	4,20E-09

When applying the proposed CF for the total forest cover loss between 1990 and 2010 for Pakistan (8400 km^2) and Mozambique (43560 km^2) a DALY of 116,61 and 2392,28 respectively was calculated. This shows that deforestation has an impact on human health through increased flood, but the impacts are small compared to the DALY numbers for flood as a total. The damage on human health for the Mozambique flood in 2000 (and the cyclone “Eline”) was 45000 DALY for comparing. This confirms that the principal flood-generating factor is rainfall intensity and duration (Chapter 2.5, Precipitation), but deforestation has a noticeable impact.

4.2 Sensitivity analysis

“Life cycle assessments require many input parameters and many of these parameters are uncertain; therefore, a sensitivity analysis is an essential part of the final interpretation.” (Groen et al, 2014).

Table 12 Sensitivity analysis of the proposed CF



Sensitivity analysis		**Change in CF value in %**	
Input parameter	**Units**	**20% increase**	**20% decrease**
Precipitation	millimeter/year	**34,70**	**-33,69**
PET	millimeter/year	-13,91	14,62
w reference	-	11,14	-14,76
w transformed	-	-13,04	15,10
Area rained on	m^2	20,00	-20,00
slope	degrees	21,26	-20,67
Flood distribution	km^2	-16,67	25,00
Flood depth	m^2	-16,67	25,00
DALY drowning	DALY	20,00	-20,00

The sensitivity analysis of the proposed characterization factor is shown in table 12 (above). For the sensitivity analysis the medium values for the Pakistan study was applied. The input variables were increased and decreased with 20 % to study the change in CF output. As table 12 shows most of the input parameters caused a change in CF output of between 11 and 25 % (absolute values). The input parameter with the highest sensitivity was precipitation with 34,7 % and -33,7 % change in CF result from a ±20 % change in input.

4.3 Uncertainties in the FF and EF

“In general, three types of uncertainties can be distinguished: measurement uncertainty, uncertainty from assumptions, and uncertainty from ignorance.” (De Schryver et al. 2001).

Fate Factor

The most sensitive of the input parameters for the FF was precipitation. A small uncertainty in precipitation causes a noticeable change in the final CF (Table 12). However, annual precipitation data is easily obtained and accurate and should therefore usually not cause uncertainties. For simplicity temporal changes in precipitation from day to day as emphasized by Heuvelmans et al. (2005) is not taken into account for the FF, this increases the uncertainties. The streamflow response to deforestation depends on both mean annual precipitation for a catchment and on the precipitation for the year under study (Brown et al. 2005). Thus annual precipitation should be used for the year under study.

Potential evapotranspiration (PET) data is obtainable globally and has a relatively low sensitivity. The plant-available water coefficient (w) is given by Sun et al. (2004) and Zhang et al. (2001) and is thus dependent on their studies. According to Osturk, Copty, Saysel, (2013) the change from forest to agricultural or urban land made the biggest impacts on the streamflow discharge. The difference in types of forests was not very decisive. They used leaf area index (LAI) and root depth (RD) as vegetation parameters and not the "w" coefficient.
Actual evapotranspiration is dependent on precipitation, the "w" coefficient and PET and can thus become uncertain. AET can also be obtained directly from global data, which can be sensible in some cases.

When multiplying the change in water yield with slope (value between 0 and 1) it reduces the output of the FF and thus reduces the CF. This is not important when comparing flood impacts from deforestation in different regions, but reduces the importance of the causal link between deforestation and flood. The magnitude of the slope factor should therefore be considered changed for further work.

Effect factor

The effect factor is generally more uncertain then the fate factor for impact assessments (Figure 1). This also applies for the EF in this thesis (Equation 10).

The quantification of human health damage caused by an increase in flood can be uncertain. The DALY values from both "Exposure to forces of nature" and "drowning" should be used with caution as mentioned in the section on LCA. Values on "Exposure to forces of nature" are lacking for many countries and also includes earthquakes, avalanches etc., and the "drowning" category mainly includes not flood related drowning. Using DALY is therefore not recommended for the effect factor, even though it is usually applied for impact assessments on human health. Applying data on people killed and displaced from flood can be an option. These data can be found in Bradshaw et al. (2007).

The flood depth parameter used when quantifying flood size in the Effect Factor is very uncertain. The damage caused by a certain depth of flood is spatially variable and reliable data can be hard to find. Comparing flood depths without considering location will lead to uncertain results: "The point at which water levels pose a risk to lives, homes, or commercial activity varies from place to place, so each site has its own set of action and flood stage water levels. As a result, absolute numbers are meaningless when comparing two locations. A river crest of 35 feet could spell disaster for a Tennessee town like Centerville, where flood stage begins at 22 feet, but pose no threat to Nashville, where flooding starts at 40 feet." (Slate, 2014). Flood depths are needed for the EF as floods typically are measured in m^2 and not m^3.

Flood distribution is the area a flood covers. Multiplied with flood depth it quantifies flood size. Flood distribution data can be uncertain as shown in the Pakistan case study where two different values were found dependent on source (Table 4, "high" and "low" values, flood distribution).

4.4 Other causes of uncertainties

In addition to causing floods, deforestation can also lead to other impacts on the water balance dependent on location. It can cause draught, as the deforested land is less capable of containing water. This leads to more floods in periods of high precipitation and reduced or no stream flows in periods of low precipitation. The natural forest works as a regulator for the water balance (Fearnside, P. 2005). Fearnside, P. (2005) also mentions that deforestation in this case of the Amazon forest, can decrease transportation of water vapor to nearby lands. When rainforest is removed it affects the local climate, less evapotranspiration leads to less clouds (water vapor) and less precipitation. This is a link between land use and water (vapor), which should not necessarily be ignored. When tropical forest is replaced by grass there will be a significant increase in surface temperature. This can lengthen the dry season and can make reestablishment of tropical forest in deforested areas difficult. Tropical forests producing water vapor are often referred to as "Cloud forests" (Lawton et al. 2001).

Flood duration

The temporal extent of a flood is a variable that will affect DALY/m^3. This is a variable that should be considered for further work. The EF could for example be divided by the average temporal extent (days) of a regions annual flood.

Time delay

When calculating increased flood risk after deforestation it should be kept in mind that there is a certain delay in the impacts on streamflows. In Ruprecht and Schofields paper (1989): *Analysis of streamflow generation following deforestation in southwest western Australia,* the first year shows a significant increase in annual streamflow relative to rainfall, and then the streamflow increases linearly for the next 7 years before reaching an equilibrium of approximately 31 % increase in streamflow after deforestation compared to prior to the deforestation. The explanation for the delay in streamflow increase was that the groundwater increased during the first years after the deforestation until it was saturated. This caused more surface runoff and more groundwater discharge with time. The streamflow relative to rainfall reached equilibrium after 7 years when groundwater levels had stabilized at a higher level then before. Both recharge and discharge of groundwater increased (Ruprecht and Schofield, 1989). This shows the importance of having a wide time horizon on the impact assessment for deforestation. When calculating the CF from deforestation the steady state conditions should therefore be used. This also applies for afforestation as newly planted trees need time to adapt and do not absorb as much water as native "established" trees (Bradshaw et al. 2007).

Snow melting

For the case study in Pakistan and the Indus river snow melting is a factor that should not be neglected. "Snowfall at higher altitudes (above 2 500 m) accounts for most of the river runoff…" (Aquastat, 2011). Large piles of snow in the mountains can cause flood as they melt during spring or summer. Floods can typically occur when snow melting and high precipitation occurs at the same time. This variable is not included in the calculations as it is a special case scenario and is not affected by deforestation. But it can make the FF more uncertain as it affects water yield through seasonal changes in precipitation.

Watershed and forest cover

The size of the deforested area relative to the catchment it is located in, is a factor that should not be neglected. It influences the relative increase in stream-flow in a watershed. A large deforested area in a small sized watershed with a small natural drainage (river size) will make a larger impact on flood risk relative to a similar sized deforestation in a larger watershed. In general, the changes in annual water yield from forest cover reductions of less than 20% of the catchment could not be detected from streamflow measurement (Brown et al. 2005). The tipping point where deforestation causes flood damage is therefore dependent on the watershed and its forest cover.

Multiplicative effect, feedback loops and tipping points

Bradshaw et al. (2007) on slope and deforestation: "high- (or low-) gradient countries experiencing heavy forest loss may have even more frequent flooding than either variable could predict additively (i.e. a multiplicative effect)." The feedback loops in the deforestation model (Figure 6) shows that it is not trivial to see the effects of an impact. If there is an instant cause and effect for the loops (negligible dynamics) they can be described with simultaneous equations ($y = f(x)$ and $x=g(y)$). Simulation will be natural if there are accumulating cause and effect relationships that can be described with integral- or differential equations. Then the temporal aspect becomes important and the timing of the impacts must be assessed. If the impacts reach "tipping-points" as could happen for the reinforcing "erosion loop", where erosion leads to floods that lead to more erosion, it can lead to huge environmental impacts.

How sedimentation of rivers and erosion can cause floods

Hilgard, O`Reilly, Sternberg, (1987) in the paper *Aggravation of Floods in the Amazon River as a Consequence of Deforestation*; discusses how both surface runoff and sedimentation of rivers causing a narrower river discharge can increase flood risk. They discuss the impact of deforestation when only a small portion of land is affected relative to the large water discharge from the Amazon River.

Leaf area index

Leaf area index (LAI) is a measure of how much of a forests area is covered by leafs. It is measured in leafs in square meters per area in square meters (Osturk, Copty, Saysel, 2013) For this thesis it is of relevance since it affects how much of the precipitation lands on the ground (this is covered in the FF by using AET). It will also decrease the raindrop speed. A low raindrop speed at ground level decreases splash erosion. LAI can also be used for assessing how many kilos of wood a square meter of forest contains.

Soil moisture

A certain amount of precipitation will lead to a different flood risk in different locations dependent on soil moisture. Bradshaw et al. (2007): "The underlying soil moisture regime can have profound effects on the frequency and severity of flooding; for example, relatively small amounts of water accumulation from rainfall in an arid region can lead to temporary flash flooding, whereas an equivalent amount of rain falling on perhumid soils may not result in any particularly noticeable accumulation of surface water…"

When the soils water holding capacity is filled surface runoff will occur. When the soil can no longer hold the excessive water, flood risk increases. The soil moisture variable thus affects flood risk. Soil moisture is taken into account when using the AET parameter, and should not be neglected.

Afforestation

The proposed CF is primarily made for deforestation, but it can also be used for afforestation. Then the FF will produce a negative value (decrease in water yield) and the CF will also become negative. A negative FF in an arid environment can lead to drought and is thus not always a desired effect. Afforestation used for flood reduction is not necessarily immediately effective, as new plants need time to root (Farley et al. 2005). Also natural "established" forests reduce surface runoff more effectively then newly planted forests (Bradshaw et al. 2007).

5 Conclusion

In this thesis the causal chains between deforestation and increased flood impacts were assessed for expanding the Life Cycle Impact Assessment methodology. LCIA and the path from functional unit to the endpoint category damage to human health were described. Then the treatment of land use and water use as separate impact categories and the links between them were assessed. The work of Heuvelmans et al. (2005) on the causal chain between land use and the water balance was reviewed, and found to be to data demanding and not globally feasible, due to the need of streamflow data. Therefore the approach of Zhang et al. (2001) and Sun et al. (2004) were applied when developing the fate factor (Equation 7 & 8). They used actual evapotranspiration (Equation 5) and annual precipitation to calculate change in water yield (Equation 4). The difference in water yield before and after deforestation was then calculated to find the change in surface runoff. Slope was used to intensify or diminish the FF. The effect factor was calculated by DALY values from “exposure to natural forces” and “drowning” relative to the size of a regions flood. When multiplying the FF and EF the CF was calculated. The CF thus gave the change in damage to human health caused by deforestation through the causal link with flood. The CF was then applied in case studies for Pakistan and Mozambique. The results for Pakistan and Mozambique were 1.39E-08 DALY/m2 and 5.46E-10 DALY/m^2 respectively. This result shows that the causal chain is important for substantial deforestations in vulnerable areas. But the results are relatively uncertain, especially the DALY and flood size data used for calculating the EFs. Further work should therefore emphasize on improving the certainties of the data applied in the EF, assess if the FF is to simplified, consider scaling the slope parameter and assess if the causal link between deforestation and flood impacts should be included in the LCIA methodology for the future.

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