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DTU Environment, October 2012

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Preface

This report was made at DTU Environment in continuation of an ongoing innovation partnership between DTU Environment, Aarhus Vand and Københavns Energi focusing on management of the urban water cycle in large cities. From Aarhus Vand the involved persons have been Anne Laustsen, Inge H. Jensen and Michael R. Pedersen, and from Københavns Energi Maj-Britt B. Poulsen and Sara Lerer.

The report is the first deliverable of the Vandsektorens Teknologiudviklingsfond project “Kvantitativt potentiale for håndtering af regnvand” co-funded by Aarhus Vand, Københavns Energi, and DTU Environment.

Lyngby, Oktober 2012

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Dansk sammenfatning

Formålet med dette studie er at kvantificere hvordan de vigtigste strømme i vandbalancer på by-niveau påvirkes af lokal regnvandshåndtering. Gennem beregninger og casestudier er potentialer udledt der inddrager drikkevandsforbrug, spildevandsproduktion, det totale nedbørsvolumen og designkriterier for anlæg der håndterer regnen. Studiet sigter efter at give et nuanceret billede af fordele og ulemper ved lokal regnvandshåndtering. Der er derfor også fokus på de udfordringer, der begrænser potentialerne. Ydermere er der som del af studiet udført et litteraturstudie og opstillet en oversigt over metode og processer med relevans for regnvandshåndtering.

Studiet bygger hovedsagligt på værdier fra vandbalancer opstillet for København (Hauger og Binning, 2006) og Aarhus (AaK, 2010b). Disse er opstillet på årsbasis og er derfor relevante i en planlægnings/forsyningssammenhæng. Tabel 1 lister de vigtigste værdier fra vandbalancerne brugt i dette studie, og de er yderligere beskrevet i afsnit 2.1.

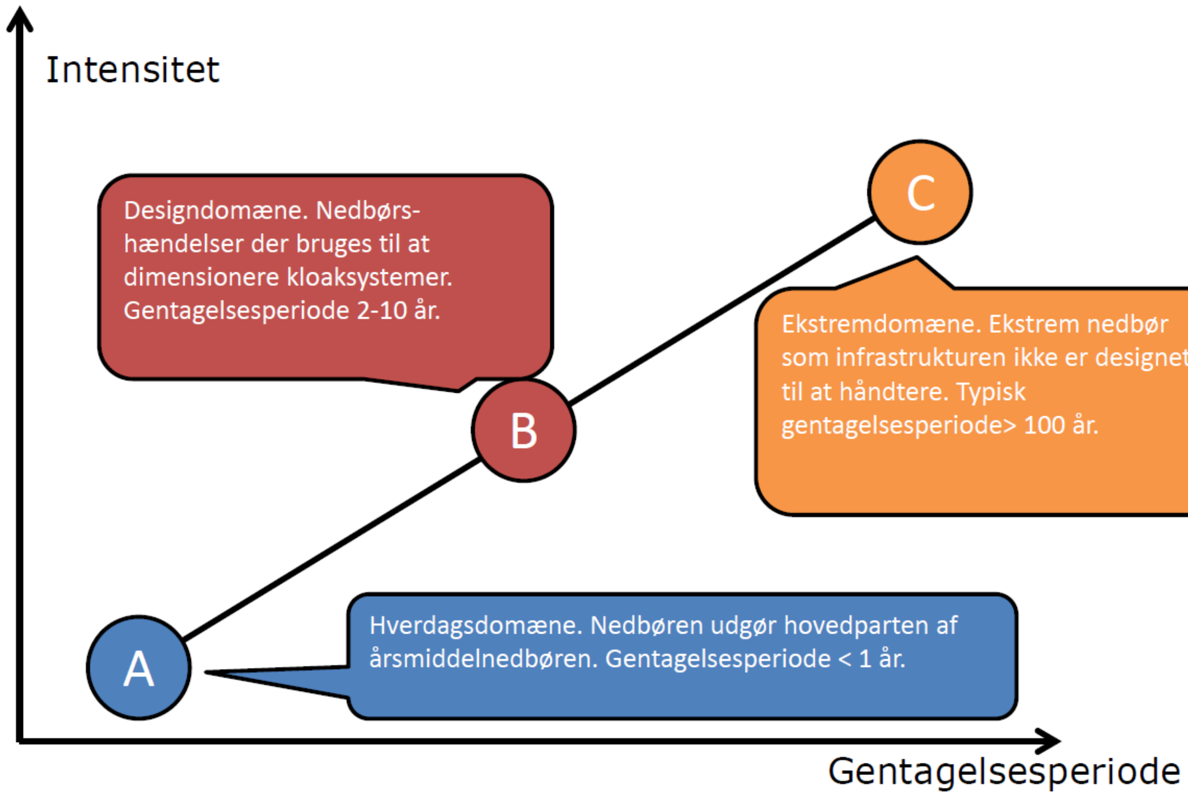
Tabel 1 Hovedstørrelser fra vandbalancerne for København og Aarhus (Hauger og Binning, 2006; AaK, 2010b).

mio.m³/år		København	Aarhus
Nedbør	$V_{\text{årlig total nedbør}}$	61,5	351
Forsynet drikkevand	$V_{\text{forsynet drikkevand}}$	32,8	18,6
Behandlet spildevand	$V_{\text{renset spildevand}}$	60,1	30
Afløb fra tage	$V_{\text{afløb fra tage}}$	6,1	4
Total nedbør til kloak og rensningsanlæg	$V_{\text{nedbør til kloak}}$	23	15

Potentialerne skal ikke kun relateres til de årlige vandbalancer, men også til det aktuelle design af det system, der skal realisere potentialet. Til dette formål er 3-punktsmetoden (3PA, Geldof, 2007; Fratini et al., 2012) tilpasset som værktøj til beskrivelse af potentialerne afhængig af hvilken slags regn anlæggene er designet til at håndtere. De tre punkter, også kaldet domæner, introduceret med 3PA er:

A. Hverdagsdomænet: normale regnhændelser som ikke giver anledning til problemer. Designkriteriet for regnvandsopsamlingstanke er brugt til at definere gentagelsesperioden for punktet. Punktet indeholder volumenmæssigt hovedparten af regnen.
B. Design domænet: punktet indeholder dimensionsgivende regnhændelser der normalt ligger til grund for design af f.eks. kloaksystemer. Den typiske gentagelsesperiode er taget fra Spildevandskomiteen (2005). Med hensyn til volumen på årsbasis er punktet mindre vigtigt end punkt A.
C. Ekstrem domænet: punktet indeholder regnhændelser som kloakker og anden infrastruktur ikke er designet til at håndtere, og som det er økonomisk urealistisk at beskytte sig fuldstændigt imod. Punktet har generelt ingen betydning hvad angår volumen på årsbasis.

De tre domæner kan fremstilles grafisk (figur 1) men det er også væsentligt at være opmærksom forskellige interessenters opfattelser af punkterne A-C (tabel 2).



Figur 1 3-punktsmetoden med beskrivelse af de enkelte domæner. Figur modificeret fra Fratini et al. (2012).

Tabel 2 Forskellige opfattelser af punkterne i 3-punktsmetoden.

	Punkt A Hverdagsdomæne	Punkt B Designdomæne	Punkt C Ekstremdomæne
Traditionel forsynings-tankegang	Bare væk med vandet	Undgå skader fra vandet	Nogle andres problem
Traditionel LAR-tankegang	Regn som ressource	Erstat lokal infra-struktur	Ikke en del af overvejel-serne
Fremspirende synspunkter	Skab øget værdi – mere at-traktive byer	Kloakker og/eller LAR?	Kontroller vandet, min-imer skader

Litteraturstudie

Formålet med litteraturstudiet er at bruge internationale erfaringer til at kvalificere de valg der er taget i studi-et og underbygge de konklusioner der er draget. Hovedkonklusionerne af litteraturstudiet i afsnit 2.2 er:

- Byens overordnede vandbalance er et vigtigt redskab til bestemmelse af flow i det urbane vand-kredsløb, og erfaringer viser at den giver et nyttigt indblik i hvor eventuelle potentialer skal findes.
- Modellering af systemer med observerede regnserier er dog essentielt for at kunne bedømme hvor-dan det aktuelle systemdesign hjælper til at opnå de identificerede potentialer.
- Velbeskrevne forbrugsmønstre er nødvendige at fastslå og inddrage i systemdesignet for at realisere potentialer for regnvandsopsamling. Dette er især tilfældet i områder som Danmark, hvor der som

udgangspunkt er rigeligt med vand. De Busk et al. (2011) viser tydeligt hvordan manglende viden om forbruget kan lede til væsentlige fejldimensioneringer med kraftig overdimensionering af opsamlings-tanke til følge.

- Der er en umiddelbar modsætning mellem systemer, der har en høj forsyningssikkerhed, altså har opmagasineret regnvand der kan forbruges når vi skal bruge det, og systemer der er optimeret til at aflede ekstreme regnhændelser. Systemer med høj forsyningssikkerhed vil være mindre effektive til at aflede under kraftige regnhændelser, mens systemer designet med henblik på at aflede kraftige regnhændelser oftere vil løbe tør for vand i tørkeperioder. Konflikten består i at forsyningssikkerhed sikres af fyldte tanke, mens tomme tanke sikrer aflastning af kloak mv. under kraftig regn.

Metoder og processer

Metoder til regnvandshåndtering kan klassificeres efter hvilke processer, de kan bidrage med i forbindelse med forsyning og aflastning (Tabel 3). Metoderne er beskrevet i detaljer andetsteds (ViB, 2011 og KK, 2011a).

Tabel 3 De vigtigste metoder ved håndtering af regnvand og deres brug af de vigtigste processer.

Processer / Metoder	Evaporation	Infiltration	Tilbageholdelse	Transport	Reference til uddybende tekniske referencer for metoder
Grøfter	X	X		X	KK (2011a): Render og grøfter
Faskiner		X	X		KK (2011a): Faskiner ViB (2011): Cirkulær faskine, Rendefaskine
Grønne tage	X		X		KK (2011a): Grønne tage ViB (2011): Grønne tage
Infiltrationsplæner, -bede og fordybninger	X	X	X		KK (2011a): Nedsivning på græsarealer, Regn-bede ViB (2011): Infiltrationsplæne, Regnbed
Åbne bassiner	X		X		KK (2011a): Tørre bassiner ViB (2011): Tørre bassiner
Permeable belægninger	X	X			KK (2011a): Permeable belægninger ViB (2011): Permeable belægninger
Damme	X	X	X		KK (2011a): Våde bassiner og damme ViB (2011): Våde bassiner
Kloakker				X	Spildevandskomiteen (2005)
Underjordiske bassiner			X		ViB (2011): Lukkede bassiner
Vadier	X	X	X		ViB (2011): Vadi

Kvantitative potentialer

De kvantitative potentialer defineres i forhold til den overordnede vandbalance for et givet byområde, se figur 3.1 i afsnit 3.1, som den fraktion af regnvandsvolumenet der håndteres i forhold til volumenerne af total nedbør, forsynet drikkevand og behandlet spildevand. Se endvidere afsnit 4.

Procentdel af total regnvolumen udnyttet:

$$P_p = \frac{V_{håndteret}}{V_{årlig\ totalnedbør}} \cdot 100\%$$

Ligning 1

Reduktion i drikkevandsforbrug:

$$P_{pw} = \frac{V_{erstattet}}{V_{forsynet\ drikkevand}} \cdot 100\%$$

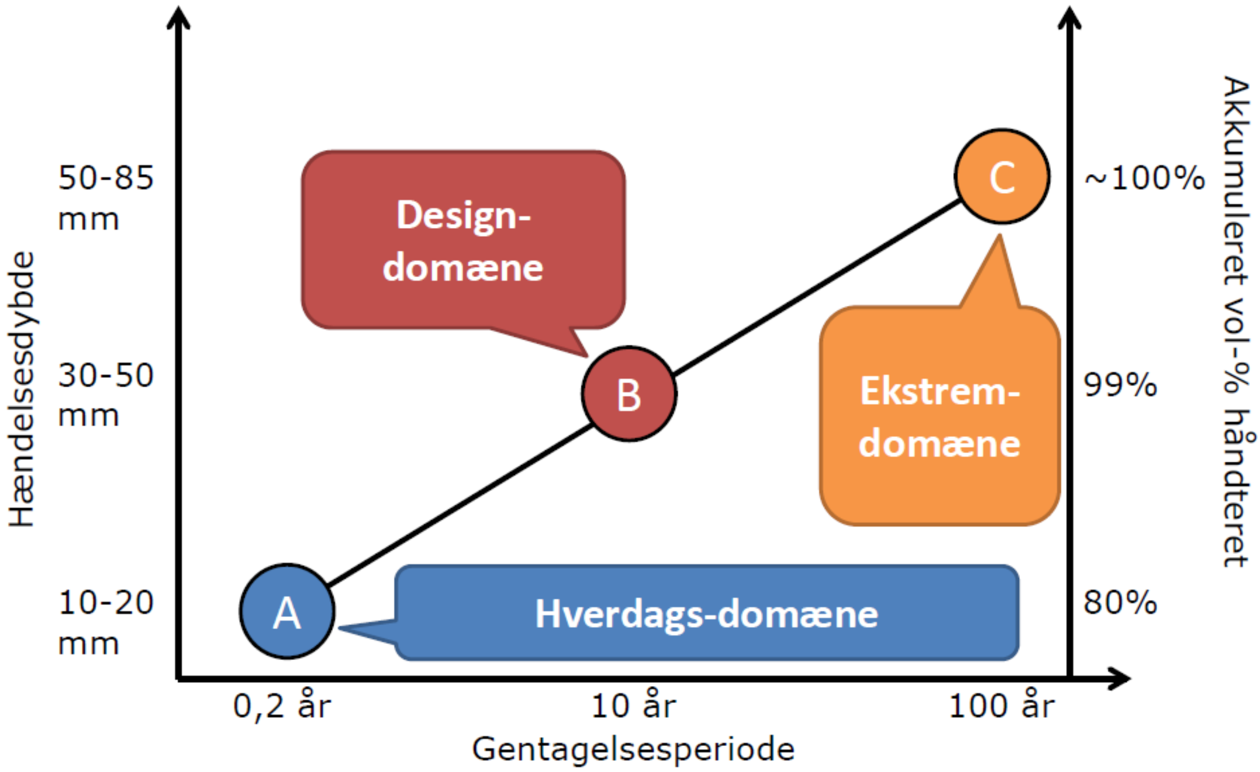
Ligning 2

Reduktion i spildevandsproduktion:

$$P_{ww} = \frac{V_{fjernet}}{V_{spildevand\ til\ behandling}} \cdot 100\%$$

Ligning 3

Bestemmelsen af det håndterede volumen kræver en klar definition og er meget afhængigt af såvel forbrugs- som nedbørsmønstret. Da systemernes virkningsgrad afhænger af regnhændelsens intensitet er 3-punktsmetode videreudviklet til at strukturere en evaluering for hvert af de 3 domæner. For at kvantificere potentialerne på baggrund af 3-punktsmetoden er det nødvendigt at definere hvert domæne i forhold til nedbørsmængde og hændelsesfrekvens. Resultaterne præsenteret i dette studie er baseret på domænerne fastlagt som angivet i figur 2. Et design efter punkt A Hverdagsdomænet håndterer langt hovedparten af nedbøren (80%) mens et design efter punkt B Designdomænet håndterer næsten al nedbøren (99%). Punkt C repræsenterer de hændelser vi ikke kan, eller af økonomiske årsager ikke vil, designe efter. Punkt C udgør kvantitativt alt regnvandet fra regnhændelser større end punkt B.



Figur 2 3-punktsmetoden med typiske dimensionsgivende størrelser for hvert punkt inklusiv andelen af regnen der forventes håndteret for et givet designniveau. Værdierne er: gentagelsesperiode (x-akse), hændelsesdybde (venstre y-akse) og andelen af årsmiddelnedbøren et design efter et givet punkt vil kunne håndtere (højre y-akse).

Casestudier

I dette studie er undersøgt tre forskellige cases der hver især tænkes implementeret i både Aarhus og København:

1. Case 1: Maksimal infiltration. Fokus er på hvad stor-skala infiltration på by-niveau af nedbør betyder i forhold til vandbalancen.
2. Case 2: Maksimal opsamling og brug. Fokus er på hvad maksimal opsamling og anvendelse af regnvand har af betydning for den overordnede vandbalance.
3. Case 3: Maksimal opsamling og rekreativ brug. Her er fokus rettet mod maksimal afkobling af regn fra fælleskloakering og behandling af regnvandet på rensningsanlæg.

Casestudierne er generelt beskrevet i afsnit 4, og resultaterne i afsnit 5. I det følgende er kun hovedresultaterne og konklusionerne bragt.

Case 1: Maksimal infiltration

Det kvantitative potentiale udregnes som infiltration af alt regnvand, der ellers ville ledes til kloak og rensningsanlæg. For København er det 23 mio. m^3/år (ud af 61,5 mio. m^3 totalt), for Aarhus 15 mio. m^3/år (ud af 351 mio. m^3 totalt). Anlægget designes til at håndtere 10-års-regn. Beregningerne viser at en stor mængde af nedbøren afstrømmer til kloak og dermed udgør et stort potentiale (tabel 4). Resultaterne viser også, at hvis anlægget kun designes til at håndtere 0,2-års regn, så falder de samlede potentialer kun med 3-4% point (afsnit 5.1). I tilfælde af at 9% af årsmiddelnedbøren infiltreres, som 2BG (2009) fandt som realistisk infiltrationsrate i København vil potentialet være tilsvarende mindre.

Tabel 4 De kvantitative potentialer for case 1: maksimal infiltration.

	København				Aarhus			
	A	B	C	Sum	A	B	C	sum
Procentdel af total regnvolumen udnyttet	30%	7%	0%	37%	3%	1%	0%	4%
Reduktion i drikkevandsforbrug	0%	0%	0%	0%	0%	0%	0%	0%
Reduktion i spildevandsproduktion	31%	7%	0%	38%	40%	10%	0%	50%

Case 2: Maksimal opsamling og brug

Det kvantitative potentiale udregnes som opsamling af alt afløb fra tage af anlæg designet efter forskrifterne til håndtering af 0,2-års-regn (KK, 2009). For København er det 6,9 mio. m^3/år og for Aarhus 4 mio. m^3/år. Resultatet er givet i tabel 5. I afsnit 5.2 er beregnet potentialer for andre grader af afkobling. Sammenhængen er lineær og afkobling af 50% af tagarealet giver potentialer på 50% af dem angivet i tabel 5.

Tabel 5 De kvantitative potentialer for case 2: maksimal opsamling og brug.

	København				Aarhus			
	A	B	C	Sum	A	B	C	Sum
Procentdel af total regnvolumen udnyttet	9%	1%	0%	10%	1%	0%	0%	1%
Reduktion i drikkevandsforbrug	17%	2%	0%	19%	17%	2%	0%	19%
Reduktion i spildevandsproduktion	9%	1%	0%	10%	11%	1%	0%	12%

Case 3: Maksimal opsamling og rekreativ brug

For case 3 udregnes potentialet ved fuld afkobling af den del af regnvandet der i dag ledes til kloak. For København er det 23 mio. m^3/år, for Aarhus 15 mio. m^3/år. Beregningerne viser her at potentialet er betydeligt (tabel 6). I afsnit 5.3 beregnes potentialer for andre grader af afkobling. Her diskuteres det endvidere, hvordan ændrede definitioner for rekreativt brug kan gøre potentialerne interessante i en større kontekst ved at inddrage løsninger uden direkte rekreativ værdi, for eksempel direkte udledning til havn eller egentlig separatkloakering som vil være mere realistiske løsninger steder hvor vandet ikke vil kunne give rekreativ værdi helt lokalt.

Tabel 6 De kvantitative potentialer for case 3: maksimal opsamling og rekreativ brug.

	København				Aarhus			
	A	B	C	Sum	A	B	C	Sum
Procentdel af total regnvolumen udnyttet	30%	7%	0%	37%	3%	1%	0%	4%
Reduktion i drikkevandsforbrug	0%	0%	0%	0%	0%	0%	0%	0%
Reduktion i spildevandsproduktion	31%	7%	0%	38%	40%	10%	0%	50%

Konklusion

De kvantitative potentialer for at opsamle og bruge regnvand som en ressource i stedet for at lede det til kloak og rensningsanlæg er generelt betydelige. Resultaterne viser at stor-skala håndtering af regnvand kan mindske drikkevandsforbruget med cirka en femtedel og mindske presset på rensningsanlæg med op til 50%.

Studiet viser endvidere at lokal håndtering af regnvand hovedsagligt håndterer hverdagsregnen, og at anlæggene herudover kun vil håndtere noget af regnen fra design domænet pg ekstrem domænet. Konkret drejer det sig om ca. halvdelen af regnen fra design domæne og en mindre fraktion fra ekstremdomænet. I forhold til de kvantitative potentialer giver alle casene attraktive resultater med hensyn til at udnytte regnvandet som ressource og begrænse flowet til renseanlæg, mens case 2 alene giver et fald i drikkevandsforbruget. Tabel 7 oplister de overordnede konklusioner på case-niveau.

Tabel 7 De overordnede konklusioner på case-niveau i forhold til 3-punktsmetoden.

	Punkt A Hverdag	Punkt B Design	Punkt C Ekstrem
Case 1: Infiltration	+	0	0
Case 2: Opsamling og brug	++	0	0
Case 3: Opsamling og rekreativ brug	+	+	0

++: casen har stor betydning for alle potentialer. +: casen har stor betydning for mindst et potentiale. 0: casen har ingen betydning for potentialerne.

1. Introduction

The purpose of this study is to quantify how local rainwater harvesting and local rainwater handling can affect the water budget for two large Danish municipalities: Copenhagen and Aarhus. Through case studies and calculations it is quantified how local rain- and stormwater management can help minimising potable water use and reduce stormwater discharge to the treatment plant. The study provides a picture of the overall benefits of local rain- and stormwater management, but also describes potential drawbacks involved herein. Furthermore the study includes a literature review to include lessons learned elsewhere and to be able to assess the importance of scale.

The three cases explored in this report is 1) a case where the maximum amount of rainwater is infiltrated, 2) a case where as much rainwater as possible is used in households or alike, and 3) a case where the rainwater is used for recreational purposes. The evaluation of the selected cases and their hydrological impact is in this report based on an adapted version of The Three Point Approach (3PA), which documents the existence of three distinct domains where decisions related to stormwater management are made (Fratini et al., 2012). This is a novel approach for stormwater management quantification, based on varying “domains” of rain events. It is relevant to use the 3PA since systems for managing rainwater and stormwater perform differently for varying magnitudes of rain events. The 3PA uses the frequency relationship observed in rainfall to classify three domains (or points) each containing a well defined part of the precipitation pattern (Figure 1.1). For each point the effect, in this case the quantitative potentials, of the cases are then evaluated.

For Danish conditions we define the three points as:

A. The everyday domain. The design criteria for rainwater harvesting and use are used to define this point (KK, 2009); with respect to the frequency relationship this gives a return period of approximately 0.2-0.33 years. Volume-wise most rainfall falls within this domain and this includes all the rainfall that normally causes no serious concern for the public.
B. The design domain. The rainfall in this domain is classified as the events the sewage infrastructure is designed to handle. For sewer systems and overflow structures this normally means rainfalls with a return period of 2-10 years depending on the structure. These rainfalls constitute a minor fraction of the annual rainfall volume.
C. The extreme domain. The rainfalls in this domain are the ones that have such a large return period that it is considered unfeasible to design piped infrastructure that handles them without disturbance to society. In this study events with return periods of 100 years are used. The annual rainfall volume in this domain is virtually zero.

The three points are perceived differently depending on the stakeholder’s background. Some of the common stakeholder interpretations are shown in Table 1.1.

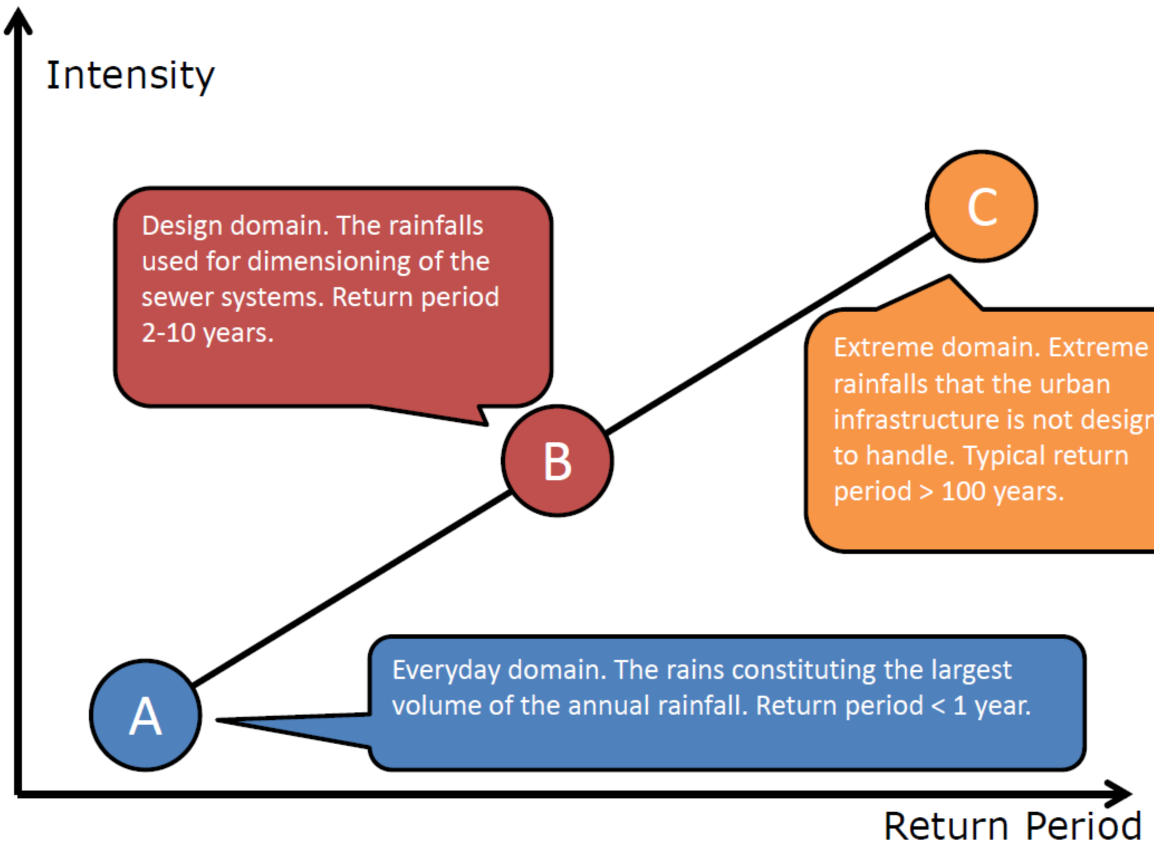


Figure 1.1 The general Three Point Approach. Modified from Fratini et al. (2012).

Table 1.1 Different perceptions of the points of the three point approach.

	Point A **Everyday domain**	**Point B** **Design domain**	**Point C** **Extreme domain**
Traditional utility thinking	Just get rid of the water	Avoid damage from the water	Somebody else's problem
Traditional WSUD thinking	Rainwater as a resource	Replace local-scale infrastructure	Not considered
Emerging views	Create added value – more attractive cities	Sewers and/or WSUD?	Control the water, minimise damage

The report structure is that first the background of the project and the state of the art according to the present literature is given in Section 2. The quantitative potentials is defined and the three points approach specified in section 3. The cases are described and qualified in section 4 and evaluated according to the quantitative potentials and the three point approach in section 5. Finally, the conclusions are given in section 6.

2. Background

2.1 Water balances for the municipalities of Copenhagen and Aarhus

Comprehensive water balances have been made for both Copenhagen and Aarhus (Hauger and Binning 2006; Aak, 2010b). Hauger and Binning (2006) developed the methodology and set up the balance for the municipality of Copenhagen. Subsequently a balance has been made for the municipality of Aarhus using the same methodology (AaK, 2010b).

The study will use annual water budgets for the two municipalities as the primary data source as these data sets are quality controlled and filtered for possible annual variation, which is especially important for the precipitation part (Hauger and Binning, 2006; AaK, 2010b). The quantitative potentials evaluated using these data sets will be associated with the mean annual precipitation and are as such relevant for planning purposes in relation to water supply or treatment. The main water flows are precipitation, supplied water, wastewater sent to treatment, roof runoff and total precipitation sent to treatment (highlighted in Figure 2.1).

Table 2.1 outlines the water balances for Copenhagen and Aarhus municipalities. The main differences between the balances arise from the different sizes of the cities and the different land uses in the municipalities. Copenhagen (74.8 km^2) has approximately twice the population of Aarhus (468 km^2), and the municipality of Aarhus covers in contrast to Copenhagen large rural areas (> 50% of total area) (Danmarks Statistik; 2012). This results in a relatively much larger precipitation volume in Aarhus compared to Copenhagen. Since the water balances are on municipality level the last issue makes it somewhat difficult to directly compare the major flows in the two water balances (Table 3.1). The main difference between the municipalities is the annual volume of precipitation; Aarhus gets almost 6 times as much precipitation as Copenhagen which is primarily due to its larger size, and partly due to a higher mean annual precipitation in eastern Jutland (722 mm) than in north-eastern Sealand (613 mm) (DMI, 2012). The internal relation between the other figures of Aarhus in Table 3.1 show that for the urban part of the municipality there is a behavioural relationship between the flows much like the one observed for Copenhagen.

Table 2.1 Main figures from the water balances for the municipalities of Copenhagen and Aarhus. From Hauger and Binning (2006) and AaK (2010b).

mill. M3/year		Copenhagen	Aarhus
Precipitation	$V_{precipitation}$	61.5	351
Supplied potable water	$V_{poatable\ water}$	32.8	18.6
Treated waste water	$V_{waste\ water}$	60.1	30
Roof runoff	$V_{roof\ runoff}$	6.1	4
Total precipitation to treatment plant	$V_{prec\ to\ TP}$	23	15

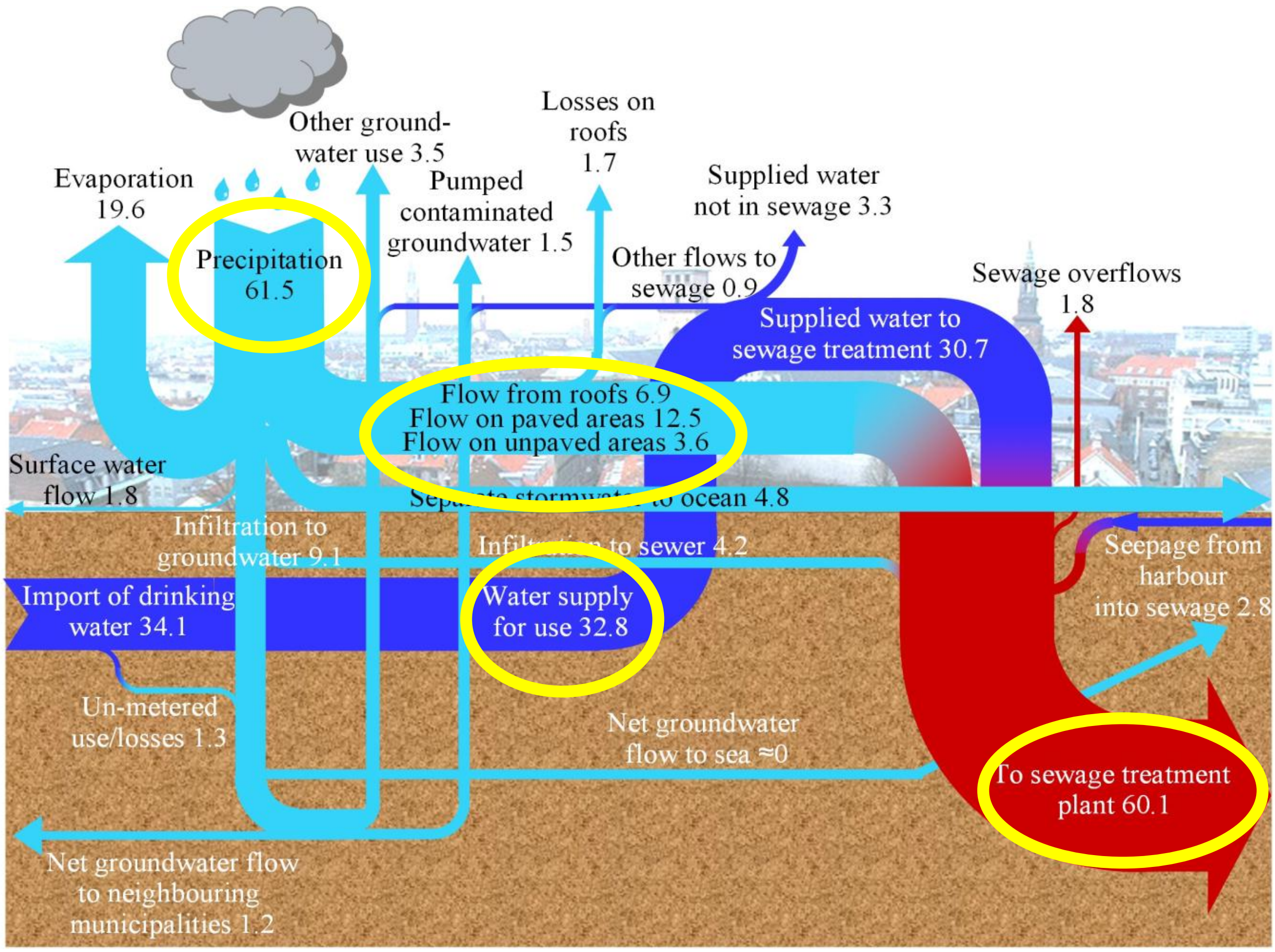


Figure 2.1 The water balance for the municipality of Copenhagen. Main flows are highlighted: precipitation, the supplied water, the water going to the treatment plant and the rainwater flows going into the sewers. Figure modified from Hauger and Binning (2006).

2.2 Literature review

Danish experience within the study field and novel international literature is summarised in this section to place this study into a wider context.

2.2.1 Danish experience

Several studies have been conducted in Denmark exploring essential aspects relevant for rainwater harvesting, handling and use. This section aims at giving a short chronological review of the Danish experience approximately through the last decade.

Albrechtsen et al. (1998) and Albrechtsen (1998) both focus on the water use in private households. Albrechtsen et al. (1998) explores the resource potential of collecting rainwater, assesses the financial aspects of doing so and calculates how it could actually impact the urban water cycle if realised. Albrechtsen (1998) is a thorough investigation of the potential microbial problems and risks associated with use of rainwater and “greywater” in households.

Hauger and Binning (2006) set up a full water balance for the municipality of Copenhagen and map the resources and uses. Furthermore, the study includes a list of major consumer categories and a list of international state of the art projects. The water balance from their study is the basis for the water balances that will be calculated in the present study. Rygaard et al. (2007; 2008) provides further insight into the international development within alternative water handling and use.

The "Black, Blue and Green – Integrated Infrastructure Planning as Key to Sustainable Urban Water Systems" project (2BG, 2009) is a major project involving several universities, utilities, municipalities and consultants. In relation to this study the most interesting part is the assessment of how much rainwater that can actually be infiltrated in western Copenhagen without harmful side effects. 2BG provides important information on the limiting factors when large scale infiltration is considered.

ViB (2011) and KK (2011a) list methods for local handling of rainwater. ViB (2011) was developed as part of a major project that focuses on changing Danish urban areas from vulnerable in a changing climate to water robust. The project involves major relevant Danish partners, both public and private.

Spildevandskomiteen holds detailed data for rainfall (e.g. Spildevandskomiteen (2011b)) and provides design guidelines for sewers and local structures for handling rainwater (Spildevandskomiteen, 2005; 2011a), regional variations in extreme rainfall (Arnbjerg-Nielsen et al., 2006) and changes in rainfall due to climate change (Arnbjerg-Nielsen, 2008).

The references above show that comprehensive knowledge within all the domains defined by the 3PA exists in Denmark, but also that the interplay between the domains is not described satisfactory.

2.2.2 International literature review

Hauger and Binning (2006) and Rygaard et al. (2007; 2008) all provide thorough description of the international state of the art within alternative water handling and use. In this study the focus has thus been on very novel studies. Much experience was collected at the "12th International Conference on Urban Drainage" in Porto Alegre, Brazil in September 2011 which hosted a dozen sessions on alternative handling, use and harvesting of rainwater and stormwater (stormwater here refers to rainwater that runs off from urban surfaces).

Worldwide precipitation is harvested and used; mostly, though, in arid regions with Australia providing much research within the field. For areas with particular focus on water resources and water sensitivity cities Kenway et al. (2011), Martínez et al. (2011) and Campisano and Modica (2011) present municipality wide case studies; Sharma et al. (2008) studies on the neighbourhood scale; and Browne et al. (2011), Hamel et al. (2011) and Trowsdale et al. (2011) present specific cases on actual systems. For a non-arid climate Belmeziti et al. (2011), Gires and de Gouvello (2009) and Itou et al. (2011) present at the municipality scale; and Ward et al. (2011), Vialle et al. (2011), Seidl et al. (2011), Martínez et al. (2011) and DeBusk et al. (2011) all assess specific cases in real systems. Most studies focus on water quantities but a few assess water quality issues as well (Vialle et al., 2011; Seidl et al., 2011; Martínez et al., 2011). Table 2.2 summarises the main findings from the international studies.

Table 2.2 Summary of international studies.

Spatial scale of study	Study focus[1]		Rainwater use	Location	Annual precipitation	Handling percentage	Reference
Regional	+	Methodology development	Toilet flushing	Sicily, Italy. 17 cities	433 – 1312 mm	20 – 100% of demand	Campasino and Modica (2011)
Municipality, regional	+	Reliability and quantitative indicator development	Toilet flushing	France. 63 cities		5 – 90% of demand	Gires and de Gouvello (2009)
Municipality. Regional	+	Quantitative performance indicators	Toilet flushing, irrigation, clothes washing	Australia. 4 cities and 1 region		0 – 22% of rain harvested	Kenway et al. (2011)
Municipality	+	Quantitative indicators and tool development	Toilet flushing and garden watering	Paris, France	730 mm		Belmeziti et al. (2011)
Municipality	*	Scenario calculations	Toilet flushing and garden irrigation	Canberra, Australia	640 mm	10 – 50% of demand	Sharma et al (2008)
Municipality	*¤	Clogging and lifetime	Infiltration	Niigata, Japan			Itou et al. (2011)
Municipality	¤	Quality performance	Different SUDS	Barcelona, Spain			Martínez et al. (2011)
Individual buildings	*	System performance	Irrigation, toilet flushing, vehicle washing, animal kennel washing and brine solution	North Carolina, USA. 6 buildings		100% Over-sized systems in general	deBusk et al. (2011)
Individual buildings	*	System performance	Toilet flushing	Exeter, UK. 1 building	807 mm	87% of demand	Ward et al. (2011)
Individual buildings	*	System performance	Toilet flushing and irrigation	Auckland, New Zealand. 1 building	1200 mm		Trowsdale et al. (2011)
Individual systems	*¤	Clogging of trenches	Infiltration	Melbourne and Brisbane, Australia. 2 systems	653 and 1172 mm		Browne et al. (2011)
Individual buildings	*¤	Quality and quantity	Toilet flushing	Sotralentz , France. 1 building	766 mm	87% of demand	Vialle et al. (2011)
Individual buildings	¤	Pathway and quality	Rainwater harvesting	Paris, France. 1 building	730 mm		Seidl et al. (2011)
Individual systems	*	Evapotranspiration and groundwater recharge	Infiltration	Melbourne, Australia. 1 system			Hamel et al. (2011)

[1] The marks group studies according to focus and the text is a further description of the individual study. The groups are (+) studies dealing with indicators and methodologies, (*) studies dealing with quantitative performance and (¤) studies dealing with qualitative performance.

City-wide cases

On the very large scale Kenway et al. (2011) presents a water balance model for cities. The model is supplemented by a number of performance indicators that relates to the flows constituting a city wide water mass balance. Belmeziti et al. (2011) present a framework to assess which buildings are important to consider for rainwater harvesting on municipality level. For a suburb of Paris only residential buildings prove to be important. Compared to harvesting from all roofs, this results in a 20% reduction in rainwater harvested. The study considers both rainwater used for toilet flushing and garden watering. Gires and de Gouvello (2009) demonstrate that for most of France, excluding the Mediterranean coastal region, well planned rainwater harvesting on single family houses can provide 50-90% of the daily demand for toilet flushing on 95% of the days in the five year period simulated. The houses considered have roof areas in the range 60-160 m^2 and storage tank volumes in the range 0.5-4 m^3. The high reliability of this leads to a 10-20% reduction in conventional water supply. Campisano and Modica (2011) shows that on the regional scale of Sicily, Italy, rainwater used for toilet flushing in domestic houses can provide approximately 70% of this specific part of the water use in areas where the annual precipitation falling on the roof is equal in volume to the annual demand for toilet flushing. If twice as much rain falls on the roof the provision rises to approximately 90%. Sharma et al. (2008) presents an Australian (Canberra) case study where rainwater harvesting is used for toilet flushing and garden irrigation. It is evaluated that tank sizes of 10-14 mm pr m^2 collection area per lot gives a reliability of 40%; meaning that 40% of the time rainwater is available for use. This setup results in a drop in potable water use of 25%. It is noted that the amount of water used for irrigation is considerably more than what would be expected for Denmark due to the climatic conditions in Australia. However, per capita potable water use is only slightly higher than what is expected for a Danish setting. Together these studies show that city-wide water balances are useful for determining the important flows in the urban water cycle (Kenway et al., 2011; Belmeziti et al., 2011). Furthermore it is shown that simulations with actual time series of rain events are necessary to determine how great a proportion of an identified potential that can actually be utilised in a more close-to-real setting (Gires and de Guovello, 2009; Campisano and Modica, 2011). Furthermore the results stress the need of considering the possible use of the rainwater and the patterns associated with this use, this will together with the overall precipitation pattern in the end determine the needed storage and degree to which the rainwater can be utilised.

Single building cases

On the building level Vialle et al. (2011) demonstrate that a 4-people typical French single family household can replace 42 m3 of potable water per year with harvested rainwater by using the rainwater for toilet flushing only. In the French example, a 5 m^3 tank collects roof runoff from an unknown roof area in a region experiencing 760 mm of annual precipitation on average. This is rather similar to what would be expected in a Danish context. Water stress was only experienced in drought periods; the periods where it must be expected that traditional water supply also is most difficult. Even though the study does not mention anything about the overflows from the tank or the roof area connected, it is concluded from the reported figures that a substantial part of the water has been overflowing in the wet season since the system provided 100% of the demand 7 months in a year and that the overall efficiency of the system in this respect might not be too good. DeBusk et al. (2011) assess the difficulties of harvesting rainwater in humid regions. The main conclusion is that in areas where water is not a sparse resource, rainwater harvesting should be organised as fully automated systems where the users do not have to make active choices to use it. Proper usage schemes should be identified to ensure use all year round and avoid long-time storage and regular overflows during wet seasons. Toilet flushing and commercial uses as car washing are highlighted as good schemes where well designed rainwater harvesting systems can be useful. Ward et al. (2011) present a study from the United Kingdom where rainwater is harvested and used for toilet flushing in an office building. The building has a 1500 m^2 flat roof, a 25 m^3 storage tank and 111 occupants. The system provided on average 87% of all water for toilet flushing and for some periods in the 8 months monitored actually 100%. De Busk et al. (2011) and Ward et al. (2011) stress the necessity of assessing the usage needs and emphasise how usage needs become even more important in areas where water is not considered a sparse resource and substantial amounts of rain water is potentially lost through overflows.

With respect to the more alternative solutions to get rid of rainwater Trowsdale et al. (2011) reports from Auckland, New Zealand. A commercial building investigated has approximately 50 mm of effective storage of the roof runoff. This makes it possible to collect more water than is used in the building on an annual basis. It also acts as an effective retention basin for the building since the tanks are emptied slowly throughout the wet period of the year. Rain water is also collected at the local car park which is connected to a bio retention unit which is again connected to a "rain garden" (a flower bed designed to optimise infiltration and/or evaporation). The runoff volume from the rain garden to the sewer system during a heavy rainfall in the dry season is reported to less than 10% of the rain falling and the peak flow only 0.45 L/s. In comparison it is estimated that the volume would have been 80% with a traditional direct connection to the sewer with a peak flow of 2.8 L/s. Hamel et al. (2011) have investigated where the rainwater entering a rain garden actually ends up. Due to low permeable soils below the top soil layer more than 70% of the water flowed laterally from the rain garden into the soils surrounding it. Here it was available for evapotranspiration. Due to the condition of the actual experiment (extremely wet period) evapotranspiration was not enhanced to a measurable degree and the water is expected to have recharged groundwater from the soil. In case of water stress situations evapotranspiration would have been able to continue at a higher level for a longer period of time due to the water available from the rain garden. These studies show how proper planning can enhance evapotranspiration due to enhanced water availability and thus potentially help removing water faster than infiltration, use or retention and transport should be able to.

System malfunctioning and water quality issues

With respect to fouling and malfunctioning of infiltration systems Itou et al. (2011) investigate the performance and difficulties of maintenance of a city-wide network of local stormwater infiltration systems. In Niigata city 53,000 stormwater infiltration inlets are placed at private properties. The study describes how the inlets deteriorate over time due to clogging with sand and soil, and that restoration is difficult and impossible without excavation. Browne et al. (2011) model the effect of clogging of stormwater infiltration trenches. Clogging has a huge impact on the performance of the trench system and the experiments used for the modelling show that the flow rate out of the trenches are reduced by up to 90% in a month. Most interesting is that trenches placed in low permeable soils – typically clays – are much less affected by clogging over time than similar trenched in high permeable sandy soils. Due to the often complicated soils in Denmark it is important to assess the actual infiltration conditions at-site as these studies suggest.

Besides physical design also water quality adds significant constrains to the potential for rainwater harvesting. Quality of the rainwater is an important aspect not covered in this report but it still constitutes a major part of the research regarding use of rainwater. Vialle et al. (2011) shows that the microbial quality of roof runoff makes it impossible to meet drinking water standards, but it does not pose a significant risk if used for toilet flushing. Seidl et al. (2011) demonstrate the importance of collecting grounds on harvested rainwater quality. A tiled roof resulted in far more polluted runoff compared to a glass roof with respect to heavy metals and organic compounds. With respect to microbial contamination, runoff from both roofs could not meet drinking water standards. Martínez et al. (2011) assess the quality of rainwater collected in different ways. The conclusion is that only roof runoff is essentially clean enough for use, but stormwater runoff from other paved surfaces can be used with simple cleaning strategies. All studies stress the fact that any implementation of rainwater harvesting or infiltration has to consider potential contamination problems arising from the alternative handling of the rainwater. It is also mentioned that consideration of treatment of the rainwater is necessary before use or infiltration to avoid potential risk for users or groundwater resources.

Summary

The international studies support the conclusion that there exist a disagreement between systems that provide availability most of the time, thus act as a stable source of water, and systems that handle most of the water (on an annual volumetric basis) but suffer from water stress in dry periods. The first system is basically designed for planners of water supply but has a substantial volume overflowing to sewers or other receiving bodies; the other system is designed for urban drainage use detaining rainwater even at the urban drainage design level but requires considerable water use in dry periods to ensure that empty storage is available at the next rainfall period, thus being of less advantage to the water supplier.

2.3 Processes and methods for handling of rainwater

In this section a catalogue of technologies and solutions relevant for rainwater harvesting and local use are presented. The aim of this catalogue is to give an overview of the concepts in rainwater harvesting and local use and the techniques facilitating the different concepts. Further details on the technologies are available elsewhere (ViB, 2011; KK, 2011a).

Depending on whether the purpose is retention, water supply, treatment, infiltration, flood prevention, etc., different processes are of importance. Considering rainwater harvesting retention is the most important process since it provides the necessary storage to match collection patterns with usage patterns. Groundwater recharge favours the process of infiltration, since this is the process actually transferring water to the subsurface, but also depends heavily on retention since infiltration is a slow process. Furthermore transport is relevant if recharge is impossible on-site. Traditional separation of stormwater from wastewater is implemented to ease the load on the sewer system and can be done using a large range of processes: evaporation, infiltration, retention and transport. All these processes either remove water from the engineered system or smooth out peak flows, enhancing management in both cases. The processes are described further in the following.

1) Evaporation. The water is transferred to the atmosphere as vapour and is as such removed from the system. In Denmark the mean potential evaporation potential is estimated to be approximately half a meter per year (ViB, 2011). To optimise evaporation water has to be available under drying conditions. Plant cover will further increase evaporation due to transpirations processes.

2) Infiltration. The process where water is transferred from the surface into the subsurface. Infiltration rates are mainly controlled by the soil properties. Generally infiltration into clayey soils is a very slow process and considerable storage capacity will have to be accompanying the infiltration system (ViB, 2011).
3) Retention, including also detention. In combination with the other processes retention can be an important process since it provides the storage capacity that allow for reasonable dimensioning of the elements that actually get rid of the water. Thus the main purpose of retention is to smooth peak loads and to provide time enough for other solutions to work (ViB 2011).
4) Transport. The process moves the problem to another location where it has to be handled. Transport is almost always necessary to some degree unless in-situ solutions are present to handle the rainwater.

In Table 2.3 a number of methods/technologies are listed and their association with the abovementioned processes marked. Most methods are associated with several processes and references for more in-depth descriptions are also provided in the table.

Table 2.3 Overview of interplay between methods and processes relevant for getting rid of rainwater both locally and centrally.

Processes / Methods	Evaporation	Infiltration	Retention	Transport	References for further technical description of methods
Ditch	X	X		X	KK (2011a): Render og grøfter
Fascines		X	X		KK (2011a): Faskiner ViB (2011): Cirkulær faskine, Rendefaskine
Green Roofs	X		X		KK (2011a): Grønne tage ViB (2011): Grønne tage
Infiltration lawns/beds/hollows	X	X	X		KK (2011a): Nedsivning på græsarealer, Regnbede ViB (2011): Infiltrationsplæne, Regnbed
Open basins	X		X		KK (2011a): Tørre bassiner ViB (2011): Tørre bassiner
Permeable surfaces	X	X			KK (2011a): Permeable belægninger ViB (2011): Permeable belægninger
Ponds	X	X	X		KK (2011a): Våde bassiner og damme ViB (2011): Våde bassiner
Sewers				X	Spildevandskomiteen (2005)
Underground basins			X		ViB (2011): Lukkede bassiner
Vadi	X	X	X		ViB (2011): Vadi

3. Definition of quantitative potentials

The quantitative potentials are constructed to relate the considered volumes to key flows in the water balance on an annual basis. Further they are conditioned on precipitation properties on the event level using the Three Point Approach (3PA) (Geldof, 2007; Fratini et al., 2012).

A potential is a relative measure and the quantitative potential (P) in connection with a rainwater or stormwater management case will be evaluated in relation to three water flows: precipitation, water supply and water to treatment plant. Figure 2.1 shows the magnitude and importance of these flows in relation to the full water balance for Copenhagen.

The percentage of total rainwater volume used (P_p) is defined as the volume of precipitation that the case is able to handle relative to the annual volume of precipitation. P_p is a measure of how well a case is able to use rainwater as a resource and is calculated as:

Percentage of total rainwater used:

$$P_p = \frac{V_{handled}}{V_{annual\ total\ precipitation}} \cdot 100\%$$

Equation 3-1

The reduction in potable water demand: (P_{pw}) is the volume of potable water replaced by rain-water relative to the current volume of potable water supplied. P_{pw} is a measure of how much a case is able to decrease the potable water demand and is calculated as:

Reduction in potable water demand:

$$P_{pw} = \frac{V_{replaced}}{V_{supplied\ potable\ water}} \cdot 100\%$$

Equation 3-2

Finally the reduction in total wastewater production (P_{ww}) is the volume of water removed from the sewage flow relative to the current flow to the treatment plant. P_{ww} describes the degree to which a case is able to ease the load on the treatment plant and is calculated as:

Reduction in total waste water production:

$$P_{ww} = \frac{V_{removed}}{V_{sevage\ to\ treatment}} \cdot 100\%$$

Equation 3-3

3.1 The three point approach

The quantitative potentials are further linked to the three point approach (3PA) by evaluating the potential regarding events in each point/domain in the 3PA. The calculations are carried out an-alysing both the typical event depth associated with each point and the annual rainfall volume as a function of return period, see Figure 3.1.

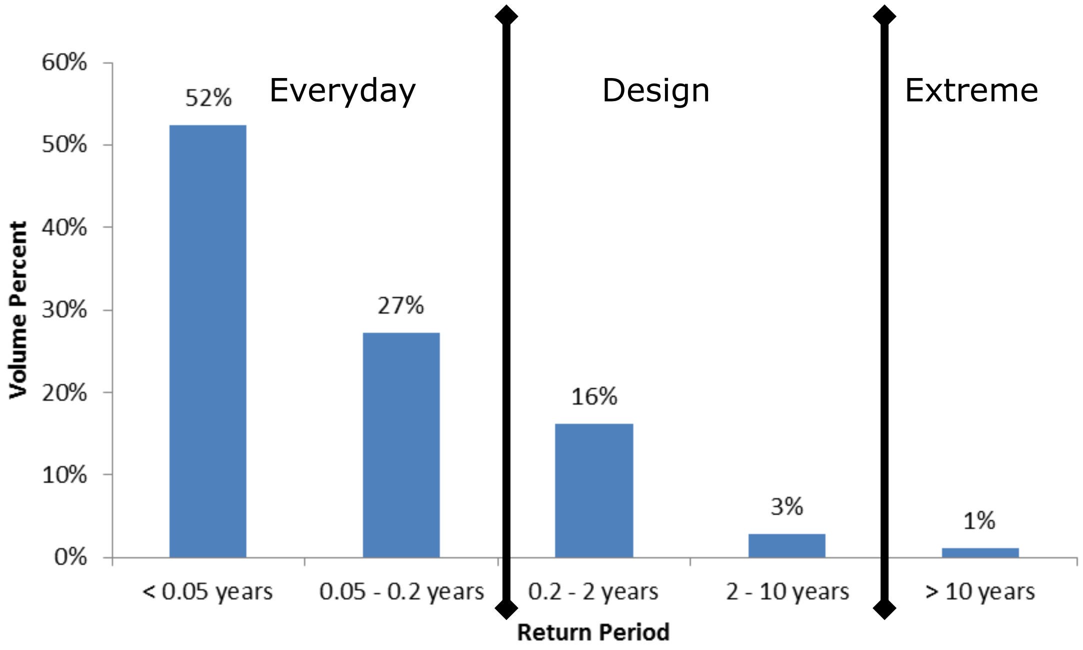


Figure 3.1 Volumetric percentages of rainfall associated with events with different return periods. The percentages only sum up to 99% due to rounding of numbers.

Most rainfall falls within domain A (Figure 3.1), less in the most frequent end of domain B (T=0.2-3 years) and small volumes (<4%) in the high end of point B (T=2-10 years)and in point C (T>10 years). These figures are indicative only, since they are subject to spatio-temporal variations, see Appendix 7.1. Even so, the general pattern is similar for rain data from all evaluated locations and for all event time frames.

Typical design storms are associated with each point. For point A, a return period of 0.2 years is chosen corresponding to the design criterion for rainwater harvesting for use (KK, 2009), for point B 10 years is chosen which is a typical design guideline for sewers (Spildevandskomiteen, 2005) and for point C 100 years is chosen as this is far more extreme than the other two and also the upper limit for the typical assessment of rainfall extremes, e.g. as considered in the Danish recommendation for analysis of rain data series (Arnbjerg-Nielsen et al. (2006)). The calculation method provided in Arnbjerg-Nielsen et al. (2006) also makes it possible to associate rainfall event depths to the design storms and for this study two definitions are chosen: the total event depth and the 3-hour event depth. The 3-hour event is chosen since three hours is a typical maximum runoff time from a large urban catchment. The two definitions lead to a span of event depths illustrating the build-in variability of precipitation for each point/domain in the 3PA. The three points can be summarised as:

A. The everyday domain. It is evaluated that approximately 80% of the annual precipitation volume falls in this category, see Appendix 7.1. Design practise for this domain is generally total event depth of 25-30 mm even though Figure 7.5 in Appendix 7.1 point to lover values (KK, 2009).
B. The design domain. These rainfalls constitute a minor fraction in the order of 3% of the annual rainfall volume (Appendix 7.1). For a 10-year event this corresponds to 32 mm in 3 hours and total depth 50 mm.

C. The extreme domain. This domain contains a negligible amount (<1%) of the average annual precipitation volume. For a 100-year event this corresponds to 54 mm in 3 hours and a total depth of 85 mm.

The 3PA is a very useful tool to describe how well a system designed for one domain is functioning under influence of design events from the others. Table 3.1 provides figures that show how large a fraction ($f_{i,j}$) of an event volume a structure can handle when faced by events with a larger return period / higher depth than the design criteria. As an example one can look at a soakaway designed to store 25 mm of rain from the attached roof (it is designed for point A). If the roof is presented with 50 mm of rain (a point B rain) the soakaway will still handle the first 25 mm but the other 25 mm will overflow from the structure. This relationship is exactly what the $f_{A,B}$ fraction of 0.5 means.

Table 3.1 Fraction of rainfall that is handled by a structure designed for a specific domain given different design depths. Point A = everyday domain, point B = design domain and point C = extreme domain.

$f_{i,j}$		***i* = design criteria**		
		Point A *Everyday*	Point B *Design*	Point C *Extreme*
***j* = event type**	Point A	1	1	1
	Point B	0.5	1	1
	Point C	0.3	0.6	1
Typical event depth (mm)		**25**	**50**	**85**

All the findings are summarised in Figure 3.2 where the following is listed for each point: return period (x-axis), typical event depth of design rain (left y-axis) and the accumulated annual percentage of the total precipitation volume a structure designed for (right y-axis).

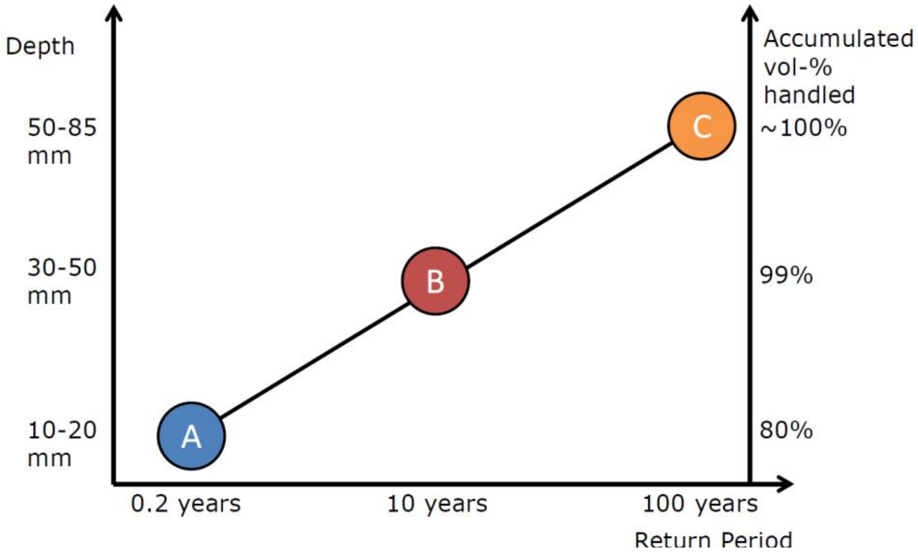


Figure 3.2 Design return periods associated with each point in the three point approach, corresponding depths and percentage of the total precipitation handled if the point is used as design standard.

3.2 Summary of quantitative potentials

For each case (see section 4) a set of criteria will be evaluated ensuring that the quantitative potentials cover the three points defined by the 3PA. Since the quantitative potentials are volumetric fractions relating to mean annual flows the sum of the quantitative potentials for each point reflect the total potential for rainwater handling for each case.

Table 3.2 Evaluation matrix for the cases. Indices for case 1 filled in.

Case 1	Point A Everyday	Point B Design	Point C Extreme	Sum
$\mathbf{P_p}$	$P_{p,1A}$	$P_{p,1B}$	$P_{p,1C}$	$P_{p,1}$
$\mathbf{P_{pw}}$	$P_{pw,1A}$	$P_{pw,1B}$	$P_{pw,1C}$	$P_{pw,1}$
$\mathbf{P_{ww}}$	$P_{ww,1A}$	$P_{ww,1B}$	$P_{ww,1C}$	$P_{ww,1}$

An overall assessment of the quantitative potentials and comparison of different cases for Aarhus and Copenhagen will be summarised quantitatively using the following marker-set and table:

- **++** : The case will be able to handle an amount of rainwater that in practise could make a difference in the management practise within the point.
- **+** : The case will act as part of a solution to handle the rainwater within the point, at least one quantitative potential stands out as marked positive.
- **0** : The case will have virtually no effect on the handling of rainwater within the point, quantitative potentials are not marked.

Table 3.3 Evaluation matrix for comparison of cases.

	Point A Everyday	Point B Design	Point C Extreme
Case 1: Infiltration			
Case 2: Harvesting and use			
Case 3: Harvesting and recreational use			

4. Cases

The three cases evaluated in this report are set up to cover three possible uses of rainwater: in-filtration, indoor use and outdoor use. This categorisation makes it possible to characterise the cases more in-depth, specify which water can be used and identify other relevant limitations that might make it impossible to realise a calculated potential in reality. The three cases are named:

1. Maximum infiltration
2. Maximum harvesting and use
3. Maximum harvesting and recreational use

With the maximums high-lighting the fact that it is potentials that are to be identified.

4.1 Case 1: Maximum infiltration

In this case the maximum amount of rainwater that can be infiltrated is quantified. Furthermore a setup where the infiltration solutions are connected to the sewer system through overflow drainage pipes is investigated.

Initially all rainwater currently intercepted by the sewer system is classified as potential water that can be infiltrated and it is calculated how much rainwater this corresponds to with respect to annual number of mm and total soakaway (infiltration trench) volume given the different design practises.

Finally a more realistic case is set up for Copenhagen using the constraints identified by 2BG (2009) as the primary boundary conditions. For the Harrestrup Å catchment on average 9% (range 0 – 30% within the catchment) of the mean annual precipitation can be infiltrated without causing problems with rising groundwater levels (2BG, 2009). Figure 4.1 gives a schematic representation of the setup of Case 1.

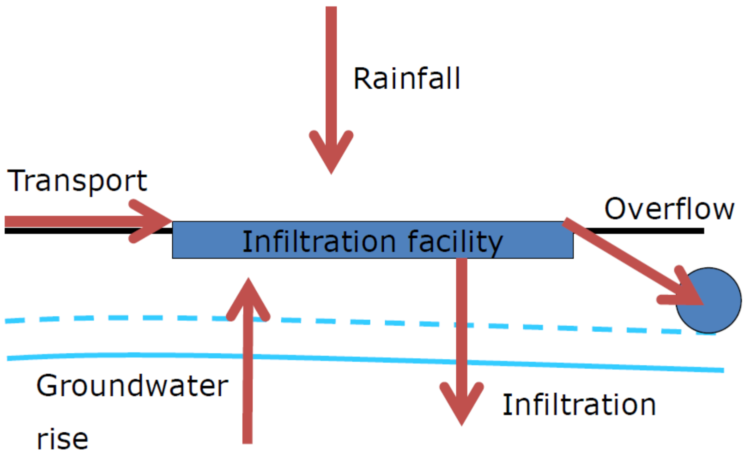


Figure 4.1 Schematic representation of Case 1.

4.2 Case 2: Maximum harvesting and use

In this case the maximum amount of rainwater that can be harvested and later used is quantified.

The case focuses on the potential for rainwater harvesting and not on identifying actual needs of the water. This means that it is quantified how much rainwater of a desired quality that can be collected and it is assumed that it can all be used. To do that the issues that has to be considered are:

1) Legislation. Only roof runoff is considered as sufficiently clean rainwater for indoor use and is thus the only rainwater considered in this case (Albrechtsen et al., 1998). Hauger and Binning (2006) suggest that 6.9 mill. m^3 of rainwater can be harvested off the roofs in the municipality of Copenhagen, constituting 11% of the mean annual precipitation falling over the entire city.
2) Storage. Since the harvesting and the use are both discontinuous processes a substantial storage capacity has to be included. General harvesting and usage schemes have to be matched to quantify the storage needs if the maximum amount of rainwater has to be harvested.

The total storage need associated with the potential will be calculated and possible challenges of use and collection will be addressed to evaluate the possible problems related to realising the potential. Figure 4.2 presents the schematic setup of Case2.

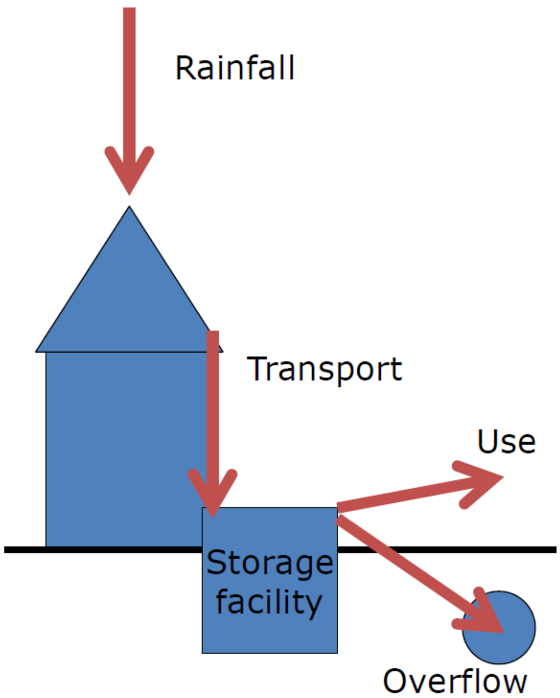


Figure 4.2 Schematic setup of Case 2.

4.3 Case 3: Maximum harvesting and recreational use

In this case the maximum amount of rainwater that can be harvested and used with recreational value is quantified. This idea origins from the current wastewater management plan in Aarhus which has the goal to separate all stormwater from the wastewater sewers (AaK, 2010a).

The main difference between this case and Case 2 is in the lack of legislation regarding water for recreational purposes. Furthermore, the water use is expected to be much more centralised and thus the storage needs may be different from Case 2. In this case all rainwater will be diverted from the sewers and used recreationally.

The case will quantify the necessary storage volume if all rainwater is disconnected and discuss possible discrepancies between collection and usage patterns. Figure 4.3 gives a schematic overview of Case 3.

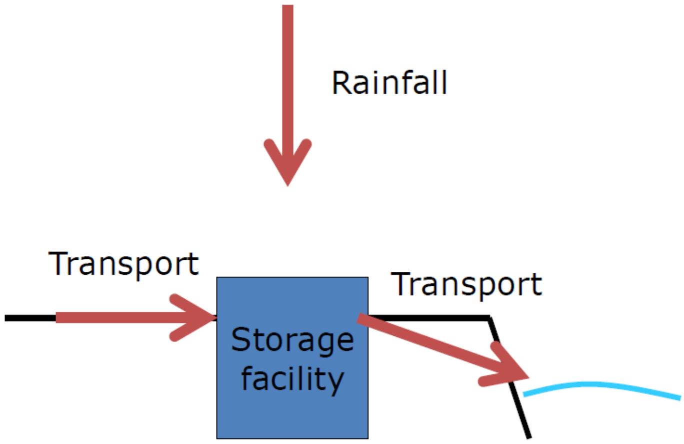


Figure 4.3 Schematic setup of Case 3.

5. Evaluation of cases

Each case is evaluated according to their quantitative potentials in the following and subsequently general issues relevant for all cases are discussed and the cases are evaluated more holistically for comparison.

5.1 Case 1: Maximum infiltration

The initial setup of Case 1 is to infiltrate all rainwater which would normally end up in the sewer system and at the treatment plant. This amount corresponds to 23 million m^3 for Copenhagen and 15 million m^3 for Aarhus (Hauger and Binning, 2006; AaK 2010b).

First a design criterion is chosen such that a 10-year event can be handled by the system, this design should in principle be able to replace existing sewer systems. This system is able to handle 37% (5%) of the total precipitation corresponding to 23 million m^3 (15 million m^3) for Copenhagen (and Aarhus in parenthesis, also onwards in the remainder of Section 5). Most of the potential is realised from the everyday events at point A where 30% (3%) is collected (18.3 million m^3 (12 million m^3)), a smaller part from point B where 7% (1%) is collected (4,4 million m^3 (2,9 million m^3)) and only a very small part from the point C events (0% (0%) and 0.12 million m^3 (0.075 million m^3)) The results regarding the quantitative potentials are presented in Table 5.1 and the calculations in Appendix 1.1.2.

Table 5.1 The full potential of infiltrating rainwater given an infiltration system designed as a stand-alone system, i.e. for a 10-year event.

	Copenhagen				Aarhus			
	A	**B**	**C**	**Sum**	**A**	**B**	**C**	**sum**
Percentage of total rainwater volume used (P_p)	30%	7%	0%	37%	3%	1%	0%	4%
Reduction in potable water demand (P_{pw})	0%	0%	0%	0%	0%	0%	0%	0%
Reduction in total wastewater production (P_{ww})	31%	7%	0%	38%	40%	10%	0%	50%

If the infiltration structure is designed to overflow 5 times per year (handling of a 0.2-year event) and the rest of the setup kept the same, the resulting potentials are as reported in Table 5.2. As expected the difference between using design criteria of 10 and 0.2 years is only in the order of 10% and is related to a decrease in the collection at point B, the sewer design domain, where only 4% (0%) is collected corresponding to 2.2 million m^3 (1.4 million m^3). For the everyday domain nothing is changed and for the extreme domain only marginally less water is collected (0.069 million m^3 (0.045 million m^3)).

Table 5.2 Quantitative potentials calculated for Case 1 for a system designed for a 0.2-year event.

	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	sum
Percentage of total rainwater volume used (P_p)	30%	4%	0%	34%	3%	0%	0%	4%
Reduction in potable water demand (P_{pw})	0%	0%	0%	0%	0%	0%	0%	0%
Reduction in total waste water production ($_{Pww}$)	31%	4%	0%	34%	40%	5%	0%	45%

Finally calculations are done for the Copenhagen case with the recommendations from 2BG (2009) with 9% of the mean annual precipitation infiltrated. This setup is achieved by designing a system for 10% of the rainwater with overflow 5 times a year. This setup will lose 10% of the design rain due to overflow and will thus result in the recommended 9%. The conclusions from 2BG (2009) are that the main limitation regarding infiltration of rainwater in Copenhagen is rising groundwater and not availability of rainwater. The result can be seen in Table 5.3. Here 8% or 4.9 million m^3 is collected at point A, 1% or 0.6 million m^3 at point B and 0% or 0.02 million m^3 at point C These more realistic quantitative infiltration potentials are 3-4 times lower than the theoretical potentials only considering availability of rainwater and estimated limitations in infiltration capacity.

Table 5.3 Quantitative potentials if 9% of the mean annual precipitation is infiltrated in Copenhagen as suggested by 2BG (2009).

	Copenhagen			
	A	B	C	Sum
Percentage of total rainwater volume used (P_p)	8%	1%	0%	9%
Reduction in potable water demand (P_{pw})	0%	0%	0%	0%
Reduction in total waste water production ($_{Pww}$)	8%	1%	0%	9%

To realise the potentials of the different sub-cases soakaway sizes have been calculated, see detailed calculations in Appendix 0 The calculations shown in Table 5.4 reveal that the design criterion has huge influence on the needed soakaway capacity. Designing for a 10-year event requires three times as much fascine volume compared to designing for a 0.2-year event even though the extra volume only provides 3-4% extra quantitative potentials.

Table 5.4 Calculated soakaway lengths pr ha connected impervious area for the different sub-cases of Case 1. Specifications regarding the details of the calculations are found in Appendix 7.2.1.

Sub-case	Design for 10-year event	Design for 0.2-year event	9% infiltration of MAP
Resulting length of fascine (m/ha)	677.8	228.0	22.5

An important issue regarding infiltration not covered in this report is the quality of the rainwater. Generally road runoff is considered too contaminated to be directly infiltrated and this aspect is not dealt with here. If very high levels of infiltration are necessary then pre-treatment of the most contaminated sources would be needed and possibly the potentials estimated here would be significantly smaller.

This case with large scale infiltration shows that the limiting factors are primarily infiltration capacity, groundwater levels and constrained space for infiltration structures. The availability of suitable rainwater quantities is of less importance.

5.2 Case 2: Maximum harvesting and use

In Case 2 rainwater is collected and used. This use could be in toilets or for washing of clothes, but this study does not deal with this aspect further, besides stating that we collect rainwater of a quality able to serve these needs. To satisfy this only roof runoff is considered for this case. The maximum potential is calculated from the assumption of full harvesting of all roof runoff, 6.9 million m^3 (4 million m^3), limited by the design criterion of 5 overflows per year as stated in the guidelines for collection and use of rainwater (KK, 2009). This assumption results in the potentials listed in Table 5.5 with 10% (1%) of total precipitation collected corresponding to (6.2 million m^3 (3.6 million m^3) mostly coming from point A events (9% (1%) and 5.5 million m^3 (3.2 million m^3)) and only marginally from point B events (1% (0%) and 0.66 million m^3 (0.38 million m^3)). It is assumed that the harvested rainwater replaces potable water. Appendix 1.1.3 holds the detailed calculations as well as calculations of the potentials if smaller, more realistic, fraction off roof is disconnected and the rainwater harvested. The relationship between the quantitative potentials and the fraction of roof disconnected is linear, thus a 50% disconnection of roof results in half of the potentials listed in Table 5.5.

Table 5.5 Quantitative potentials for Case 2: Full harvesting and use of roof runoff with a design criterion of handling of a 0.2-year event.

	Copenhagen				Aarhus			
	A	**B**	**C**	**Sum**	**A**	**B**	**C**	**Sum**
Percentage of total rainwater volume used (P_p)	9%	1%	0%	10%	1%	0%	0%	1%
Reduction in potable water demand (P_{pw})	17%	2%	0%	19%	17%	2%	0%	19%
Reduction in total waste water production (P_{ww})	9%	1%	0%	10%	11%	1%	0%	12%

Following current guidelines (KK 2009) and to realise the full potential for rainwater harvesting in Copenhagen a total capacity of 300 to 400.000 m^3 decentralised storage will have to be installed (Appendix 0).

Several issues prevent these potentials from being realised. Current legislation states that rainwater cannot be used in toilets and for washing clothes if collected from roofing felt roofs, asbestos containing roofs, thatched roofs, metal roofs and any roof lined with gutters of cupper or zinc (KK 2009). According to Albrechtsen et al. (1998) felt roofs constitute 16% of the total roof area in Denmark, asbestos containing roofs 50%, thatched roofs 1% and metal roofs 7%. To this percentage the roofs equipped with cupper and zinc gutters have to be added, resulting in virtually no roofs being fit for collecting rainwater. Albrechtsen et al. (1998) list various arguments in favour of including asbestos roofs as suitable for collecting rainwater. Including asbestos roofs change the conclusions significantly in favour of rainwater collection. A further limitation exist in a Danish context since it is illegal to use rainwater in public buildings and buildings with public access. The tight Danish regulations make it virtually impossible to collect rainwater on large scale without dispensation (KK, 2009).

Another important issue is matching of usage and harvesting. The rainwater tanks act as a buffer to attenuate the collection pattern and secure that rainwater is available when needed. This will work for a well-defined system, but if the total amount of collected rainwater does not match the amount used it might pose some problems. Traditionally rainwater harvesting has primarily been recommended for single family houses since these have a large roof area pr inhabitant. This results in systems that on average will harvest much more rainwater than what is actually needed for use. As an illustrative example a single-family house with a roof area of 200 m^2 could be considered. Presuming a mean annual precipitation of 700 mm, a collection efficiency of 80% and four inhabitants living in the house only using the rainwater for toilet flushing with a consumption of 9 m^3/year/person (Teknologisk Institut, 2002), the annual volumes are:

$$V_{harvested} = 150m^2 \cdot 0.7m \cdot 0.8 = 87m^3$$

and

$$V_{used} = 4 \cdot 9m^3 = 36m^3$$

Thus, 51 m^3 of rainwater is collected but never used. If large scale water harvesting shall approach the maximum potential, systems where the usage patterns and amounts are matched closely to the harvesting potentials will have to be developed. Instead of designing systems where potable water seldom has to be added due to lack of rainwater, design of systems should aim at utilising as much of the collected rainwater as possible.

Case 2 show that on the municipality scale enough rainwater can be collected from roofs to supply all water for e.g toilet flushing. However, this would require large decentralised storage facilities to match rain and usage patterns. In addition, this case would also require redistribution of rainwater between houses or even building blocks, for example from detached houses to multi-storey houses.

5.3 Case 3: Maximum infiltration and recreational use

Case 3 is set up as a “full disconnection” case meaning that initially all rainwater today ending up in the sewers is handled and used for recreational purposes. As such the potentials are easy to calculate and the result is given in Table 5.6.

Table 5.6 Quantitative potentials for Case 3: Full disconnection of all water from impermeable surfaces and use for recreational purposes.

	Copenhagen				Aarhus			
	A	**B**	**C**	**Sum**	**A**	**B**	**C**	**Sum**
Percentage of total rainwater volume used (P_p)	30%	7%	0%	37%	3%	1%	0%	4%
Reduction in potable water demand (P_{pw})	0%	0%	0%	0%	0%	0%	0%	0%
Reduction in total waste water production ($_{Pww}$)	31%	7%	0%	38%	40%	10%	0%	50%

These potentials are practically impossible to reach and calculations for several fractions of disconnection are given in Appendix 1.1.4 along with the full calculations for the case.

Recreational use is as such not defined in this report, but could be discharged into existing streams, or creation of artificial streams or ponds. Common for these uses are that when the urban infrastructure receives a lot of rainfall so do the streams. Therefore some kind of attenuation facility, temporary storage, will have to be installed to handle large scale disconnection. If full disconnection is realised the volume of these temporary storages will be of approximately the same size as today's urban drainage detention basins since they will have the same purpose in the stormwater system. Especially if areas far away from the recreational areas are disconnected, the system would have to include vast piped and possible pumped systems to bring the water from the collection grounds to the recreational areas.

A more practical way of looking at "recreational use" could be to define it as collection and release without treatment. This way the case could also include separate collection of rainwater and direct release to the harbours available in both Aarhus and Copenhagen. This would probably be a much more realistic scenario since densely build areas line the harbour in both cities and discharge of stormwater would influence the water level in the harbours much less than if discharge to streams or lakes.

Finally, if rainwater is used in fountains or similar structures (with recreational value) the quantitative potential in relation to potable water would be positive since these structures would normally be functioning using potable water. The value is not calculated here as it is considered to be insignificant in relation to the full water balance for the municipalities.
Case 3 is only realisable if the thought of recreational use is expanded to include massive transportation of rainwater to places where it can provide recreational value and avoid cost of treating rainwater in the waste water treatment plant.

5.4 Influence of climate and other changes in the future

The quantitative potentials here are all calculated based on historic data. Several of these inputs are expected to change in the future and thus, the potentials are to be considered non-stationary. Climate change is changing the precipitation patterns (Arnbjerg-Nielsen, 2009) and water efficient technologies and public engagement may continue to change water use patterns, as experienced historically (Winther et al. 2010).

A climate change induced change in precipitation is expected to result in both more precipitation on an annual basis and on more precipitation falling as extreme precipitation (Arnbjerg-Nielsen, 2009). With everything else status quo, the predicted change in precipitation pattern will increase all potentials as the roof and total runoff volumes both are expected to be linearly correlated to the annual precipitation volume.

Water saving technology and public awareness regarding water savings has already resulted in significant reductions in the potable water use. This trend might result in some further reductions although probably not of the same magnitude as have been seen in the past. A decrease in potable water use will directly increase the quantitative potentials related to potable water, and also the ones related to waste water treatment since the used potable water constitutes half of the water going to the treatment plant.

5.5 Summary

Table 5.7 summarises the calculated potentials for the cases in Aarhus and Copenhagen. Generally all the cases have the potential to handle the everyday rains in point A, which is what is expected since this is current design practice when handling precipitation locally.

Case 1 (infiltration) rainwater is generally available for infiltration. The limitations regarding the practical realisation of the potential are mostly related to soil-type and groundwater table issues. Clayey soils and high groundwater tables prevent this case to be realised. Given these limitations it is evaluated that it is not feasible to construct infiltrations systems able to handle rainfall with large return periods and the case is thus only positively marked for point A, see Table 5.7, and only with “+” since the potable water consumption is not reduced by this case.

Case 2 (harvesting and use) is the only case that gets a benefit from reducing potable water demand and is thus the only case earning the “++” mark at point A (see Table 5.7). Furthermore, the quality demand of rainwater used in households is believed to be incompatible with long-time storage and large systems able to handle more extreme rainfall, and the case is not having a marked impact on either points B or C.

Case 3 (harvesting and recreational use) is the only case where it seems favourable to implement a design able to handle events belonging to point B, the design domain, and hence it is the only case where a positive impact is expected (Table 5.7). Due to its inability to affect the potable water demand, the case only scores “+” in points A and B.

With respect to point C none of the solutions are designed to handle these points and none of them are expected to do so. Despite this, Case 3 is expected to have positive influence on the damage related to point C simply due to the fact that flooding with “pure” stormwater is associated with a lower cost than flooding with sewage.

Table 5.7 Overall evaluation of the cases ability to handle rainwater originating from events belonging to the different domains of the three point approach.

	Point A Everyday	Point B Design	Point C Extreme
Case 1: Infiltration	+	0	0
Case 2: Harvesting and use	++	0	0
Case 3: Harvesting and recreational use	+	+	0

++: The case has marked positive potentials. +: The case has at least one positive potential. 0: The case has no influence on the potentials.

6. Conclusions

The Three Point Approach, dividing the rainfall into domains (points) related to different design practises, provide an excellent way of identifying and assessing which types of rain a given case will handle. This way one can distinguish between Everyday, Design and Extreme rains and quantify the case's quantitative impact for each point/domain as well as for the full water balance.

The international experience within the area highlights the fact that most systems presently regard rainwater either as a resource or as a problem. Merging of the two is beginning to happen but generally very little experience exists as of today.

This study suggests that large-scale alternative rainwater handling has great influence on the water balances for both Copenhagen and Aarhus. Both Cases 1 and 3 highlight that disconnection of rainwater for either infiltration of recreational use greatly reduces the total load on the wastewater treatment plant with potential reductions in the produced wastewater up to 38-50%. Case 2 furthermore shows that there exist a significant potential for collection and use of rainwater. Collection and use of roof runoff alone could potentially reduce the potable water use with up to 19% and at the same time reduce the waste water production with 10-12%. The differences between Copenhagen and Aarhus are mostly due to the difference in land use in the two municipalities; for the urbanised part of the municipalities very similar potentials are expected and the results support this expectation.

The Three Point Approach has been useful to show that in the rare situations where rain falls as extreme events alternative handling systems including infiltration, rainwater collection and recreational use will not be able to handle all the water alone. In these extreme situations alternative water handling systems described in this report can only be regarded as supplements to measures specifically designed to handle severe rain situations.

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7. Appendices

7.1 3PA calculations

7.1.1 WinRegn

The percentile of volume of rain that falls within events at the three different points of the 3PA is calculated using WinRegn (PH-Consult, 2011).

Four different rain series are used for the calculations all taken from the publicly available rain series used for Skrift 28 (Arnbjerg-Nielsen et al. 2006) available at Spildevandskomiteen (2011b). All series are of similar length (approximately 17 years), two are from eastern and central Jutland and two are from the Copenhagen area, see Table 7.1. A dry weather period of 3 hours is used to separate individual rain events; this corresponds to a typical runoff time for a large urban area and is evaluated to be a good comparison timeframe for the present study.

Table 7.1 Rain series used in the study.

Station number	Name	Corrected length (years)	Mean Annual Precipitation (mm)
22421	Silkeborg Vandværk	17.10	720
23321	Kolding Renseanlæg	17.30	765
30314	Kongens Enghave	17.25	615
30316	Måløv Renseanlæg	17.13	610

WinRegn is used to rank the rain events in the series and to calculate the volume of the events. Table 7.2 summarises the volumetric percentiles that events with return periods smaller than ten, two, 0.2 and 0,05 years constitute.

Table 7.2 The percentiles of rain volume that falls as a T-year event or a less severe event.

	Jutland		Sealand		
Station/ Return period	22421	23321	30314	30316	mean
10-year	99%	99%	98%	98%	99%
2-year	97%	97%	95%	95%	96%
0.2-year	81%	83%	78%	77%	80%
0.05-year	54%	56%	50%	49%	52%

The figures of Table 7.2 and Figure 7.1 say that approximately 99% of the rain falls as less severe rain than a 10-year event, 96% as less severe rain than a 2-year event, 93% as less severe rain than a 12-month event and 80% as a less severe rain than a 5-in-1-year event. There is presumably a difference between Jutland and Sealand but the size of the difference is evaluated to be insignificant given only the four rain series. Furthermore, a difference is observed when different event definitions are used, Figure 7.2 illustrates the difference appearing when dry weather periods of 3, 12 and 24 hours are modelled. The difference is notable but the pattern is the same as observed in Figure 9.1. An important implication of this analysis is that the volume of rainwater falling as a 100-year event is negligible.

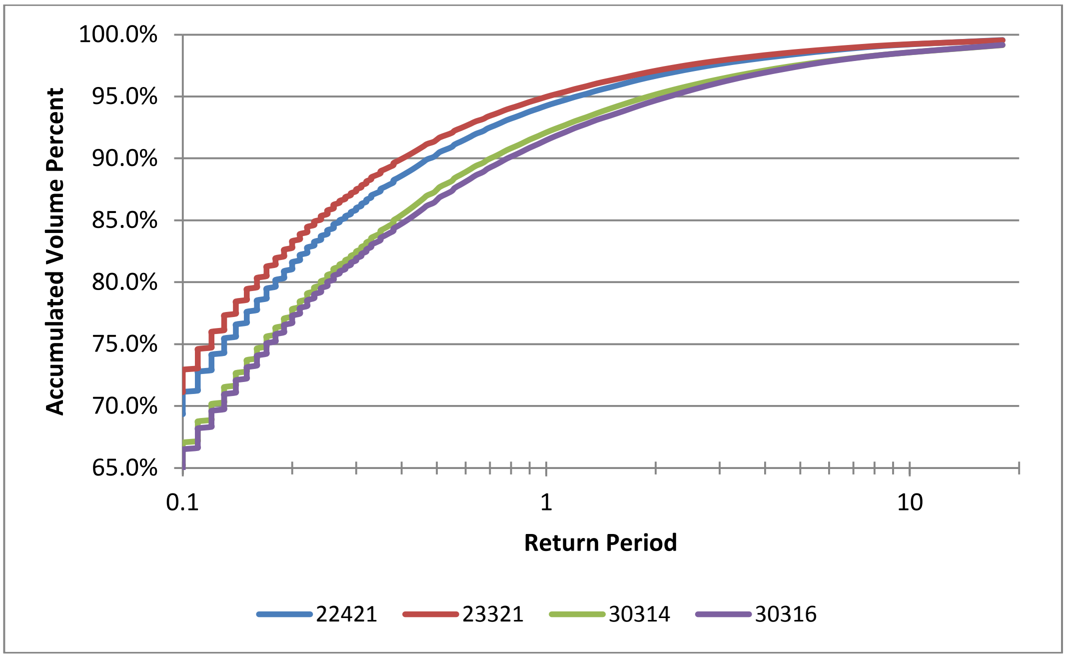

Figure 7.1 The accumulated volume of rain events less than a given T-year event for the four rain series. 3-hour event definition. Illustration of spatial variation.

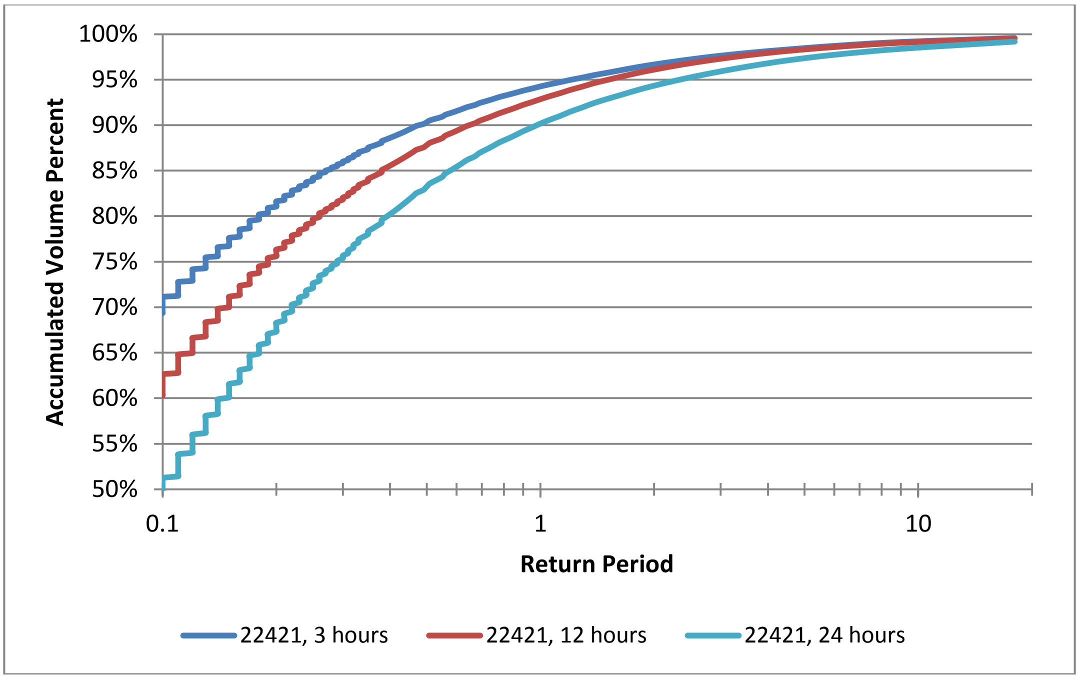

Figure 7.2 The accumulated volume of rain events less than a given T-year event for the four rain series. Different event definitions at one single station. Illustration of temporal variation.

Sorting out the numbers in Table 7.2 reveals how big a proportion of the rain that falls within a certain group of return periods; see Figure 7.3. These figures reveal that most of the rain volume is attributed to small rains and that major rains only contribute marginally to the total volume.

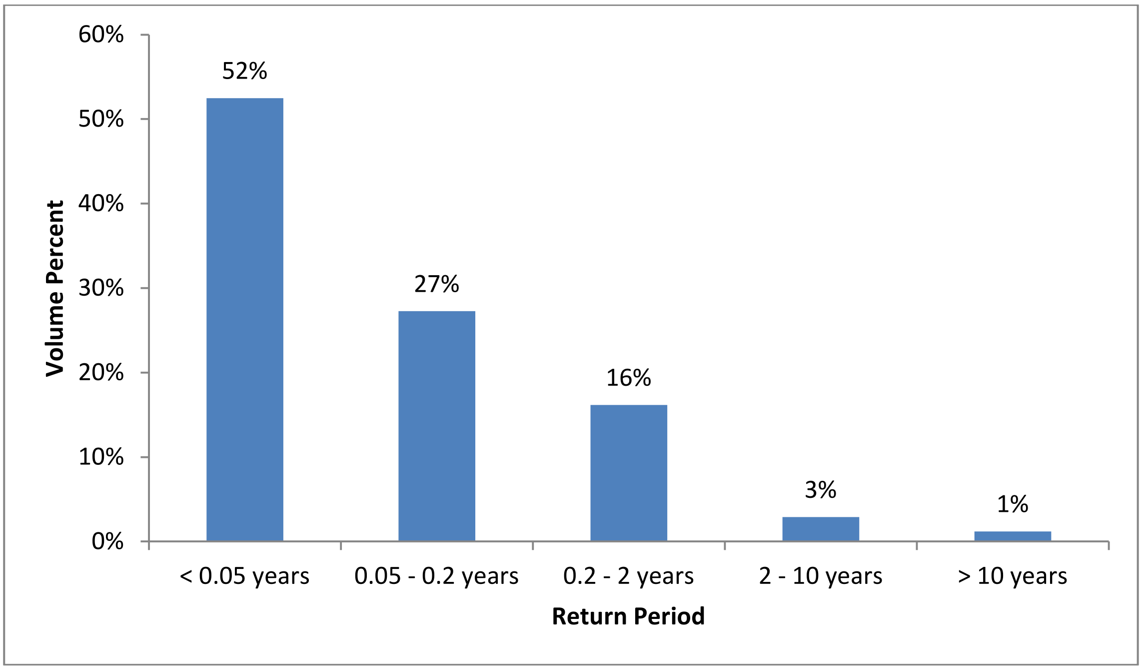

Figure 7.3 Volumetric percentage of rainwater that falls as rain with a given return period.

1.1.1 Skrift 28

The spreadsheet provided by Arnbjerg-Nielsen et al. (2006) for calculation of regional extreme precipitation is used to calculate the depth of the 3-hour design rains associated with the three points of the 3PA. For the calculation a mean annual precipitation of 686 mm (as in Hauger and Binning (2006)) and region 2, East Denmark, is used.

The three design rains have return periods of 0.2, 10 and 100 years and equal length of 3 hours. From Figure 7.4 the intensities are read as 1, 3 and 5 µm/s respectively giving 3-hour depths of 11, 32 and 54 mm.

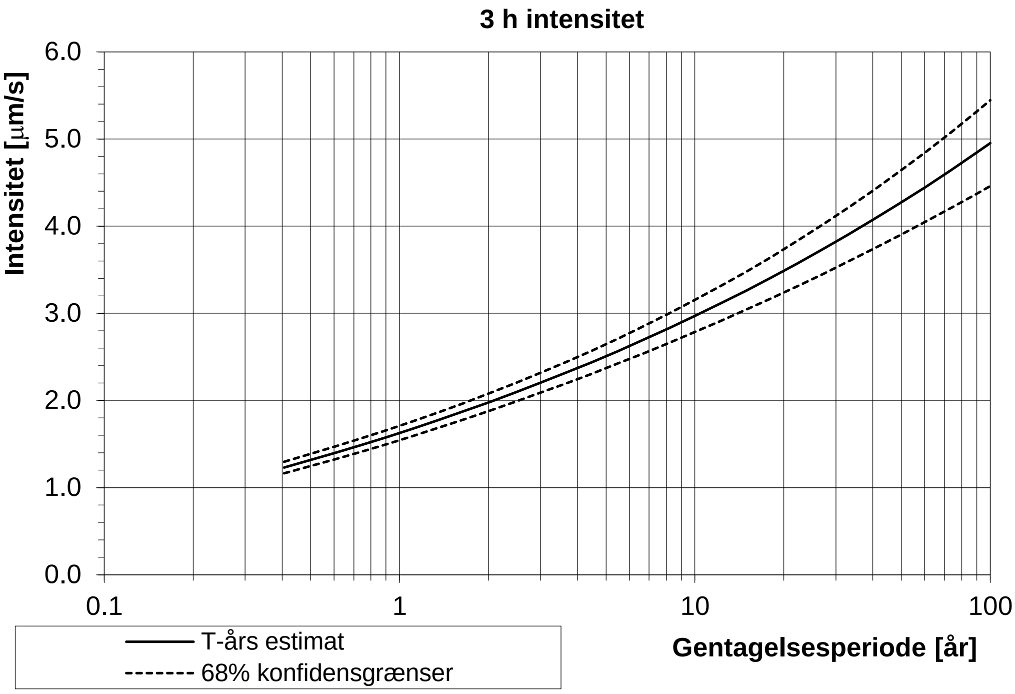

Figure 7.4 return periods and associated intensities for a 3-hour rain. Calculated with Spildevandskomiteen (2006) following Madsen et al. (2009).

From the spreadsheet values for events depths are further extracted, see Figure 7.5, which gives depths of 20, 50 and 85 mm for return periods of 0.2, 10 and 100 years.

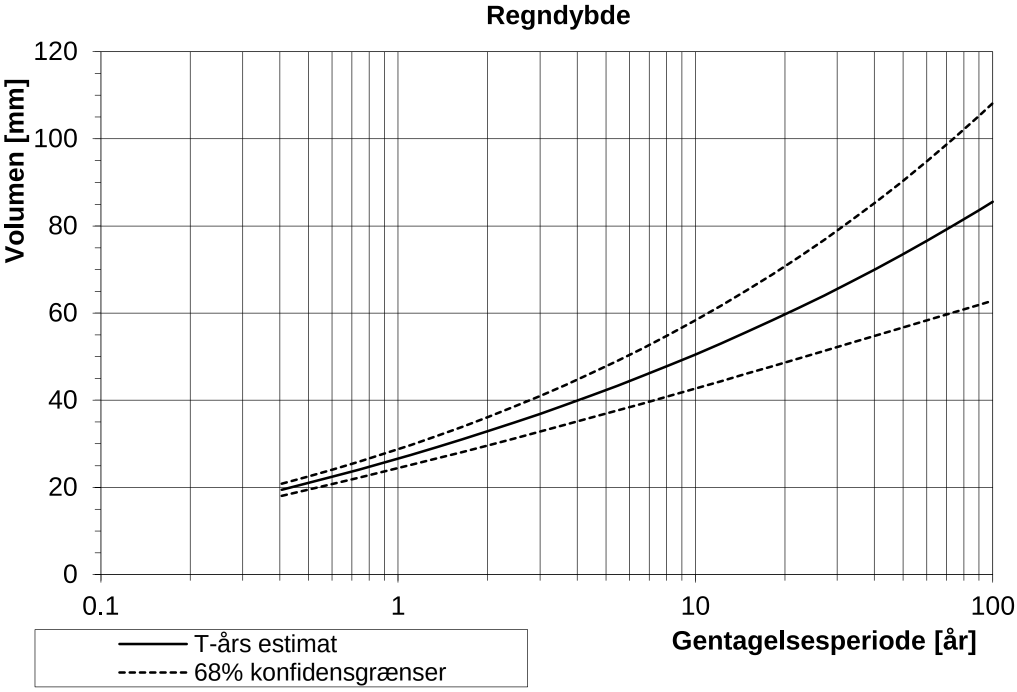

Figure 7.5 Return period for event depths. Calculated with Spildevandskomiteen (2006) following Madsen et al. (2009).

7.2 Calculation of potentials

A number of values are shared among all cases. These are the annual volumes from the water balances, Table 7.3, and the design handling fractions, Table 7.4. Furthermore, all potentials will be calculated using customised variants of Equation 3-1, Equation 3-2 and Equation 3-3, but no further references to these equations will be made in this appendix.

Table 7.3 Main figures from the water balances for the municipalities of Copenhagen and Aarhus. From Hauger and Binning (2006) and AaK (2010b).

mill. M3/year		Copenhagen	Aarhus
Precipitation	$V_{precipitation}$	61.5	351
Supplied potable water	$V_{poatable\ water}$	32.8	18.6
Treated waste water	$V_{waste\ water}$	60.1	30
Roof runoff	$V_{roof\ runoff}$	6.1	4
Total precipitation to treatment plant	$V_{prec\ to\ TP}$	23	15

Table 7.4 Fractions of water handled at a point drawn from the three points approach given the design criteria also related to the three point approach.

$f_{i,j}$	$f_{i,A}$	$f_{i,B}$	$f_{i,C}$
$f_{A,j}$	1	1	1
$f_{B,j}$	0.5	1	1
$f_{C,j}$	0.3	0.6	1

1.1.2 Case 1: Maximum infiltration

Full infiltration of all rainwater currently ending up at the treatment plant ($V_{prec\ to\ TP}$) and designed to handle a rain event with a return period of 10 years. The equations are set up as:

Precipitation:

$$P_{p,i} = \frac{V_{prec\ to\ TP}}{V_{precipitation}} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Potable water:

$$P_{pw,i} = \frac{0}{V_{potable\ water}} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Wastewater:

$$P_{ww,i} = \frac{V_{prec\ to\ TP}}{V_{waste\ water}} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

The results for both Copenhagen and Aarhus are given in Table 7.5.

Table 7.5 Results of case 1 with full infiltration and design for point B.

	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	sum
P_p	30%	7%	0%	37%	3%	1%	0%	4%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	31%	7%	0%	38%	40%	10%	0%	50%

Full infiltration of all rainwater currently ending up at the treatment plant ($V_{prec\ to\ TP}$) but only designed to handle a rain event with a return period of 0.2 years. The equations are set up as:

Precipitation:

$$P_{p,1} = \frac{V_{prec\ to\ TP}}{V_{precipitation}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

Potable water:

$$P_{pw,i} = \frac{0}{V_{potable\ water}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

Waste Water:

$$P_{ww,i} = \frac{V_{prec\ to\ TP}}{V_{waste\ water}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

The results are given in Table 7.6.

Table 7.6 Results of case 1 with full infiltration and design for point A.

	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	30%	4%	0%	34%	3%	0%	0%	4%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	31%	4%	0%	34%	40%	5%	0%	45%

The recommendation from 2BG (2009) is implemented with 9% infiltration of the mean annual precipitation $V_{precipitation}$ and a design that only handles events with a return period of 0.2 years.

Precipitation:

$$P_{p,i} = \frac{0.1 \cdot V_{precipitation}}{V_{precipitation}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

Potable water:

$$P_{pw,i} = \frac{0}{V_{potable\ water}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

Waste Water:

$$P_{ww,i} = \frac{0.1 \cdot V_{precipitation}}{V_{waste\ water}} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A,B,C\}$$

The results are given in Table 7.7. Only Copenhagen is evaluated with these restrictions since high levels of groundwater is only considered a problem here.

Table 7.7 Results of case 1 with infiltration of 9% of the total precipitation volume and design for point A.

	Copenhagen			
	A	**B**	**C**	**Sum**
P_p	8%	1%	0%	9%
P_{pw}	0%	0%	0%	0%
P_{ww}	8%	1%	0%	9%

Calculation of soakaway sizes for Case 1

All calculations are done with the spreadsheet provided by Spildevandskomiteen (2011a). Three setups are used and the values that are fed into the calculations are listed in Table 7.8. Only the return period and impermeable are is varied between the different sub-cases. All calculations are carried out for region 2 (eastern Denmark) and for a mean annual rainfall of 700 mm (not too different from what is expected in both Aarhus and Copenhagen).

Table 7.8 Input and output regarding soakaway design using Spildevandskomiteen (2011a).

8. Sub-case	9. Design for 10-year event	10. Design for 0.2-year event	11. 9% infiltration of MAP
Mean annual precipitation (mm)		700	
Region		2	
Return period (year)	10	0.2	0.2
Safety factor		1.1	
Impermeable area (m2)	10000	10000	1000
Hydraulic conductivity (m/s)		0.000001	
Fascine Width (m)		1	
Fascine Height (m)		1.3	
Fascine Fraction of cavity		0.95	
Resulting length of Fascine (m)	677.8	228.0	22.5

1.1.3 Case 2: Maximum harvesting and use

In case 2 only the roof runoff is evaluated. The potential is evaluated in relation to different fractions of disconnection ($f_{disconnection}$) as:

Precipitation:

$$P_{p,i} = \frac{V_{roof\ runoff}}{V_{precipitation}} \cdot f_{disconneted} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Potable water:

$$P_{pw,i} = \frac{V_{roof\ runoff}}{V_{potable\ water}} \cdot f_{disconneted} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Waste Water:

$$P_{ww,i} = \frac{V_{roof\ runoff}}{V_{waste\ water}} \cdot f_{disconneted} \cdot f_{i,A} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

With $f_{disconnected}$ taking the values of 1, 0.75, 0.50 and 0.25. The design situation is following the design practise with overflows every 0.2 year (Design for point A) (KK, 2009). The results are given in Table 7.9 to

Table 7.12.

Table 7.9 Results of case 2 with use of roof runoff, full disconnection and design for point A.

$f_{disconnected} = 1$	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	9%	1%	0%	10%	1%	0%	0%	1%
P_{pw}	17%	2%	0%	19%	17%	2%	0%	19%
P_{ww}	9%	1%	0%	10%	11%	1%	0%	12%

Table 7.10 Results of case 2 with use of roof runoff, 75% disconnection and design for point A.

$f_{disconnected} = 0.75$	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	7%	1%	0%	8%	1%	0%	0%	1%
P_{pw}	13%	1%	0%	14%	13%	2%	0%	14%
P_{ww}	7%	1%	0%	8%	8%	1%	0%	9%

Table 7.11 Results of case 2 with use of roof runoff, 50% disconnection and design for point A.

$f_{disconnected} = 0.50$	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	4%	1%	0%	5%	0%	0%	0%	1%
P_{pw}	8%	1%	0%	9%	9%	1%	0%	10%
P_{ww}	5%	1%	0%	5%	5%	1%	0%	6%

Table 7.12 Results of case 2 with use of roof runoff, 25% disconnection and design for point A.

$f_{disconnected}$ = 0.25	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	2%	0%	0%	3%	0%	0%	0%	0%
P_{pw}	4%	0%	0%	5%	4%	1%	0%	5%
P_{ww}	2%	0%	0%	3%	3%	0%	0%	3%

Calculation of tank size for Case 2

Dimensioning of tanks for collection of all rainwater in Copenhagen following the guidelines of KK (2009) gives: 25-30 l per m2 roof or 6% of the realisable annual precipitation. The realisable annual precipitation is set to 80% of the total roof runoff. The total roof area in Copenhagen is 13.3 mil m2 (KK, 2011b). This gives a total volume of decentralised storage of:

$$V_{storage\ (\min)} = 0.025m \cdot 13.3 \cdot 10^6 m^2 = 0.33 \cdot 10^6 m^3$$

$$V_{storage\ (\max)} = 0.030m \cdot 13.3 \cdot 10^6 m^2 = 0.39 \cdot 10^6 m^3$$

$$V_{storage\ (\%)} = 0.06 \cdot 0.80 \cdot 6.9 \cdot 10^6 m^3 = 0.33 \cdot 10^6 m^3$$

1.1.4 Case 3: Maximum harvesting and recreational use

In case 3 the total rainwater runoff is evaluated. The potential is evaluated in relation to different fractions of disconnection ($f_{disonnection}$). The design situation evaluated is for a stand-alone system, which means it has to be able to handle 10-year events (design for point B).

Precipitation:

$$P_{p,i} = \frac{V_{pre\ c\ to\ TP}}{V_{precipitation}} \cdot f_{disconneted} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Potable water:

$$P_{pw,i} = \frac{0}{V_{potable\ water}} \cdot f_{disconneted} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

Waste Water:

$$P_{ww,i} = \frac{V_{pre\ c\ to\ TP}}{V_{waste\ water}} \cdot f_{disconneted} \cdot f_{i,B} \cdot 100\%, for\ i\ in\ \{A, B, C\}$$

With $f_{disconnected}$ taking the values of 1, 0.75, 0.50 and 0.25. The results are given in Table 7.13 to Table 7.16.

Table 7.13 Results of case 3 with recreational use of all runoff, full disconnection and design for point B.

$f_{disconnected}$ = 1	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	30%	7%	0%	37%	3%	1%	0%	4%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	31%	7%	0%	38%	40%	10%	0%	50%

Table 7.14 Results of case 3 with recreational use of all runoff, 75% disconnection and design for point B.

$f_{disconnected}$ = 0.75	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	22%	5%	0%	28%	3%	1%	0%	3%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	23%	5%	0%	29%	30%	7%	0%	37%

Table 7.15 Results of case 3 with recreational use of all runoff, 50% disconnection and design for point B.

$f_{disconnected}$ = 0.50	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	15%	4%	0%	19%	2%	0%	0%	2%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	15%	4%	0%	19%	20%	5%	0%	25%

Table 7.16 Results of case 3 with recreational use of all runoff, 25% disconnection and design for point B.

$f_{disconnected}$ = 0.25	Copenhagen				Aarhus			
	A	B	C	Sum	A	B	C	Sum
P_p	8%	2%	0%	9%	1%	0%	0%	1%
P_{pw}	0%	0%	0%	0%	0%	0%	0%	0%
P_{ww}	8%	2%	0%	10%	10%	2%	0%	12%