Norges miljø- og biovitenskapelige universitet
Fakultet for Realfag og teknologi

Philosophiae doctor (ph.d.)
Thesis 2021:36

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Ås 2021

Avhandling nr 2021:36
ISSN 1894-6402
ISBN 978-82-575-1807-3

Annerkjennelser

Først av alt vil jeg takke Asker kommune og Forskningsrådet for økonomisk støtte til dette forskningsprosjektet. En offentlig PhD har blant annet til hensikt å tette noe av gapet mellom offentlig sektor og forskningsmiljøene. Jeg har gjennom arbeidet mitt lært å både verdsette og respektere begge miljøer og å anerkjenne hvor stor nytte ulike verdener kan ha av hverandre.

Videre vil jeg rette en stor takk til alle gode kollegaer i Asker kommune for innspill og sparring gjennom de årene hvor jeg har kombinert jobb og studier. En spesiell takk til alle på kommunalteknisk avdeling/vann og vannmiljø for en variert, innholdsrik og morsom arbeidshverdag. Jeg er heldig som har dere som kollegaer.

Det er mange personer jeg ønsker å takke spesielt for den støtten jeg har fått gjennom PhD- arbeidet. Det har betydd mye at dere alle sammen har hatt troen på meg:

Først og fremst vil jeg takke hovedveilederen min Harsha Ratnaweera for oppmuntring og konstruktiv veiledning, og gode tilbakemeldinger underveis i arbeidet. Du gav meg tidlig troen på at dette prosjekt var mulig å gjennomføre. Begge biveilederne mine Oddvar Lindholm og Jarle Bjerkholt var til stor inspirasjon under sivilingeniør studiene mine og har også nå under PhD-studiet bidratt med kyndig veiledning og hjelp. Uten dere hadde jeg antakelig ikke fullført studiene mine i første omgang. Jeg er beæret over å kjenne tre så viktige fagpersoner i vann- og avløpsmiljøet.

Fra NMBU vil jeg også takke Knut Kvaal for å ha gitt meg litt innsikt i statistikkens verden. Du gjorde arbeidet med artikkel nummer to til en berikelse.

I Asker kommune vil jeg spesielt trekke frem Kari Ekerholt og Per Øystein Funderud for en urokkelig tro på muligheter i stedet for begrensninger, og fordi spillerommet alltid er stor. Jeg vil også takke Eivind Dalevold for sparring og utallige diskusjoner.

Andre personer i heiagjengen som fortjener en spesiell takk er Karin og Paul Jenssen, Hilde Jenssen og Lene Ulstein. Uten dere alle vet jeg ikke om jeg hadde kommet i mål noen sinne. Det samme gjelder tidligere studievenner som alltid bidrar med klare hoder og klokskap når det røyner på.

Takk også til Julia Kvitsjøen og Rita Ugarelli, som begge er viktige fagpersoner i vann- og avløpsmiljøet. Dere gjør en forskjell for flere enn meg.

Helt til slutt ønsker jeg å takke familien min, med Tormod Sola i spissen. Uten dine helt spesielle pappa- skills ville jeg ikke fått verken tid eller rom til å gjennomføre dette prosjektet. Tusen tusen takk for tålmodighet, barneoppdragelse, middagslaging og heiarop.

Det aller viktigste jeg sitter igjen med etter disse 4 årene med studier er nye bekjentskap og enda bedre vennskap.

INNHOLDSFORTEGNELSE

Figur liste

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List of Acronyms/Ordliste

BTV	Betalingsvillighet
CBA	Cost-Benefit Analysis
CC	Climate Change
CCTV	Closed-Circuit Television
DANVA	Dansk Vand- og Spildevandsforening
DTS	Distributed Temperature Sensing
GIS	Geographic Information System
NOK	Norwegian Kroner/Norske Kroner
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
PC	Principal Component
PCA	Principal Component Analysis
pe/PE	personal equivalents/Personal Equivalents
ToT-P	Total Phosphorus/Total Fosfor- verdi
VEAS	Vestfjorden Avløpsselskap
WTP	Willingness To Pay
WWTP	Wastewater Treatment Plant

Publikasjonsliste

Følgende artikler er en integrert del av det foreliggende arbeidet.

Artikkel 1:

Kristin Jenssen Sola, Jarle T. Bjerkholt, Oddvar G. Lindholm and Harsha Ratnaweera (2018)
Infiltration and Inflow (I/I) to Wastewater Systems in Norway, Sweden, Denmark and Finland

Water **2018**, 10, 1696; doi:10.3390/w10111696

Artikkel 2:

Kristin Jenssen Sola, Knut Kvaal, Jarle T. Bjerkholt, Oddvar G. Lindholm, and Harsha Ratnaweera (2019)
Identifying factors influencing Infiltration and Inflow-water (I/I-water) in wastewater system using multivariate data analysis

Vann **2019**, 04, ISSN 0042-2592

Artikkel 3:

Kristin Jenssen Sola, Jarle T. Bjerkholt, Oddvar G. Lindholm and Harsha Ratnaweera (2020)
Analysing consequences of Infiltration and Inflow water (I/I-water) using Cost Benefit Analyses

Water Science and Technology 2020, 82.7

Artikkel 4:

Kristin Jenssen Sola, Jarle T. Bjerkholt, Oddvar G. Lindholm and Harsha Ratnaweera (2021)
What effect does traditional rehabilitation of wastewater pipelines have on the share of Infiltration and Inflow water (I/I-water)?

Sendt inn til Urban Water Journal 15-01-2021

Sammendrag

Fremmedvann har fått et økt fokus både i Norge og i internasjonale forskningsmiljø de siste årene. Likevel har veldig mange norske kommuner fortsatt veldig høye andeler fremmedvann i avløpsnettet. Undersøkelser av fremmedvannmengder inn til de største avløpsrenseanleggene i Norge viser at nivået som et gjennomsnitt lå på 66% i 2016. Dette er en nedgang fra 70% i 2009. Andelene inn til undersøkte anlegg i Danmark viser ett stabilt nivå på ca. 30%. I Sverige har det vært en reduksjon fra 58% til 46% fra 2010 til 2016, mens nivået inn til finske anlegg ligger stabilt på om lag 40%.

Vannbalanseberegninger basert på målinger av vannføring i avløpsnettet samt undersøkelser av hvor fortynnet avløpsvannet er, er enkle metoder som kan brukes for å undersøke andelene fremmedvann i avløpsnettet. Jevnlige undersøkelser av status er viktig for å kunne slå fast hvorvidt investerte midler driver utviklingen i riktig retning.

Systematisk arbeid mot fremmedvann bør starte med en analyse av hvilket nivå andelene fremmedvann ligger på, dernest en analyse av konsekvensene av fremmedvannet. For å få et riktig bilde av konsekvensene må faktorer som ofte ikke prissettes i vann- og avløpsbransjen inkluderes i regnskapet. Resipientkvalitet, utrygghet for oversvømmelse og omdømme er eksempler på sånne faktorer. Undersøkelser av betalingsvillighet

kan være gode verktøy for å få en pekepinn på hvor høyt befolkningen verdsetter for eksempel god resipientkvalitet.

I en kostnadseffektivitetsanalyse av tiltak som retter seg mot konsekvenser av fremmedvann, kommer rehabiliteringstiltak ut som det beste alternativet. En viktig forutsetning for dette er at vi rehabiliterer 20% av ledningsnettet for å oppnå 50% reduksjon av fremmedvann. Dersom vi må rehabilitere så mye som 26% av ledningsnettet for å oppnå 50% reduksjon, vil både oppdimensjonerings- og fordrøyningstiltak være like kostnadseffektive som rehabiliteringstiltak, ifølge beregninger gjort for Asker kommune.

Det er ved hjelp av tiltakskostmetoden, og hvor det er sett på en fornying av alle antatt dårlige rør, beregnet at fremmedvann kostet Asker kommune 138 millioner kroner i 2017.

Nedbør er en viktig påvirkningsfaktor når det gjelder fremmedvann. Områder med høy årsnedbør har ofte høye andeler fremmedvann i avløpsnettet. Også andre faktorer spiller en rolle i hvor høye fremmedvannsnivåene er. Undersøkelser viser at andeler drikkevannslekkasjer, kjøpt andel drikkevann fra vannbehandlingsanlegg, alder på avløpsledninger samt andel fellessystem påvirker fremmedvannsandelene i avløpsnettet. For Asker er det beregnet at utlekket drikkevann utgjør 10-15% av grunnbelastningen av fremmedvann i lange tørrværsperioder. Det er også beregnet at innlekket grunnvann kan utgjøre så mye som 25-30% av fremmedvannsmengdene i tørrværsperioder.

Rehabilitering er en mye brukt metode for å hindre fremmedvann å trenge inn i avløpsrør, mens oppdimensjonering og fordrøyning kan redusere uønskede konsekvenser av fremmedvann. Undersøkelser av tre ulike rehabiliteringsområder i Asker viser at rehabilitering av ca. 10% av ledningsnett og 10% av kummer innenfor målesonen gir en begrenset reduksjon av fremmedvannsandelene. Rehabilitering av avløpsledninger gav ikke reduksjon i overløpsdrift. For å kunne få betydelige reduksjoner av fremmedvann er det antatt at må man rehabilitere betydelig større andeler av avløpsnettet, enn det man har fått gjort i denne undersøkelsen.

Siden andelene fremmedvann i stor grad er styrt av nedbør kan innføring av kontrollområder være et nyttig hjelpemiddel for å vurdere om gjennomførte tiltak har gitt effekt på fremmedvannsnivåene eller ikke.

Abstract

In recent years there has been an increased focus on Infiltration and Inflow water (I/I-water) both in Norway and internationally. Nevertheless, the amounts of I/I-water are still very large in many Norwegian municipalities. The share of I/I-water, calculated based on the total amounts of wastewater delivered to the largest wastewater treatment plants (WWTP) in Norway, show that the level as an average was 66% in 2016. This is a decrease from 70% in 2009. The shares of I/I-water into examined WWTPs in Denmark is stable on approx. 30%. In Sweden there has been a reduction from 58% to 46% from 2010 to 2016, while the level in Finnish WWTPs is stable at about 40%.

Water balance calculations based on measurements of water flow in the sewage network as well as examinations on how diluted the wastewater is are simple methods that can be used to investigate the proportions of I/I-water in the wastewater network. Regular investigations of the status are important to determine whether invested funds contribute to a positive development or not.

Systematic work against I/I-water should start with an analysis of the status, then an analysis of consequences. To fully understand the consequences, factors that are often not priced in the water and wastewater industry must be included in the accounts. Recipient quality, insecurity for flooding and governance reputation are examples of such factors. Surveys of willingness to

pay (WTP) can be valuable tools for valuing, for example, good recipient quality.

In a cost-effectiveness analysis of measures that address the consequences of I/I-water, rehabilitation measures emerge as the best alternative. An important prerequisite for this result is that 20% of the pipeline network had to be rehabilitated to achieve a 50% reduction in I/I-water. If as much as 26% of the pipeline network had to be rehabilitated to achieve a 50% reduction, both upsizing and retention will be as cost-effective as rehabilitation measures, according to calculations made for Asker municipality.

By using the abatement cost method, where the considered measures is rehabilitating all pipes assumed to be in bad condition, it is estimated that I/I-water did cost Asker municipality NOK 138 million in 2017.

Precipitation is an important influencing factor on I/I-water. Areas with high annual precipitation often have high proportions of I/I-water in the wastewater system. Other factors besides precipitation may also contribute to I/I-water. Investigations show that leakages from drinking water pipes, the share of purchased drinking water from drinking water treatment plants, the age of wastewater pipes and the share of combined systems, all affect the proportion of I/I-water. For Asker municipality, it is estimated that leakages from the drinking water pipes contribute to 10-15% of the basic load of I/I-water during long dry periods. It is also estimated that infiltrated groundwater may account for as much as 25-30% of the amount of I/I-water during dry weather periods.

Rehabilitation is a commonly used method to prevent I/I-water from entering wastewater pipes while upsizing and retention may reduce unwanted consequences of I/I-water. Investigations of three different rehabilitation areas in Asker show that rehabilitation of approx. 10% of sewer pipelines and 10% of the manholes within a zone give only a limited reduction of I/I-water. Rehabilitation of wastewater pipes did not result in a reduction in overflow operations. To be able to obtain significant reductions in amounts of I/I-water, it is assumed that significantly larger proportions of the wastewater network must be rehabilitated than what was done in this study.

Since the amounts of I/I-water are influenced by precipitation, the introduction of control areas can be a useful tool for assessing whether implemented measures effected the amounts of I/I-water or not.

Forord

Denne avhandlingen er en del av Forskningsrådets ordning som kalles «offentlig PhD». Asker kommune inngikk i 2017 en avtale med NMBU og Norges Forskningsråd om et forskningsprosjekt som skulle se nærmere på fremmedvann i avløpsledninger.

Hensikten med en offentlig PhD er å forene det arbeidet som gjøres i det offentlige med forskningen. Jeg har 20 års erfaring med vann og avløpsarbeid i både offentlig og privat sektor, men jeg har aldri tidligere vært involvert i forskningsarbeid, utover enkelte delutredninger og analyser.

Det gjøres veldig mye godt og faglig solid arbeid utenfor forskningsinstitusjonene. Dette arbeidet deles villig i ulike fora og mellom offentlige etater, og det er stor vilje blant kommunene til å samarbeide. Likevel blir dette arbeidet i liten grad systematisert og dokumentert, og verdifulle analyser blir ikke samlet eller tilgjengeliggjort utenfor egen organisasjon. På forskningssiden er erfaringsgrunnlaget mitt mye mindre enn innen offentlig sektor, men etter 4 år i forskningsmiljøet sitter jeg igjen med den motsatte opplevelsen enn fra det offentlige. Her er forskere og andre veldig opptatt av å få publisert arbeidene sine, men det betyr absolutt ikke at resultatene blir tilgjengeliggjort for allmennheten. Kanskje heller det motsatte. Språket blir innviklet, engelsk er en terskel for mange, og resultatene er generelt sett lite tilgjengelig for folk flest.

Mitt mål med det arbeidet jeg har gjort gjennom denne doktorgraden har vært å dokumentere og systematisere noe av det gode arbeidet som blir gjort i vann- og avløpsbransjen. Jeg har også prøvd å tilgjengeliggjøre resultater slik at andre kan ha nytte av alle de timene jeg har lagt ned. Jeg har derfor utført undersøkelser som jeg lenge har tenkt at burde vært gjort, men som jeg aldri tidligere har hatt tid til å sette meg skikkelig inn i. Jeg har og prøvd å bruke figurer og språk som gjør undersøkelsene lette å forstå.

Det er mange norske kommuner som har veldig store utfordringer knyttet til fremmedvann, men akkurat hvor skoen trykker mest varierer fra sted til sted. Det er store geografiske forskjeller og det er vanskelig å komme med entydige svar. Jeg tenker det viktigste som kommer ut av det arbeidet jeg har gjort gjennom PhD- løpet er å sette enda mer fokus på fremmedvann og å dannet et bedre grunnlag for videre arbeid.

Gjennom arbeidet mitt har jeg avdekket kunnskapshull som ligger utenfor mitt arbeid. Arbeidet mitt er derfor ett lite bidrag i et større puslespill.

1. Introduksjon

1.1. Struktur på avhandlingen

Kapittel 1 i denne avhandlingen gir en oversikt over det arbeidet som er gjort. Hensikten med kapittel 1 er å introdusere temaet fremmedvann.

Hensikten med kapittel 2 er å sette enkeltarbeidene i system og å gi en total oversikt over arbeidene som er gjort.

Kapittel 3 omhandler ulike metoder som er brukt. Kapittelet gir også en oversikt over datafangst og sier noe om datakvalitet.

I kapittel 4 oppsummeres de resultatene som er funnet. Det legges vekt på refleksjoner rundt mulige feilkilder og forbedringspotensial i resultatene.

I kapittel 5 diskuteres utsikkerheter.

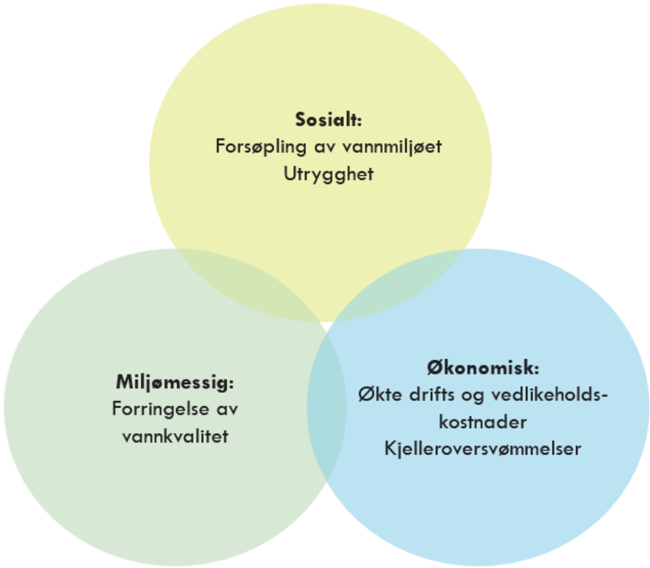
Kapittel 6 trekker konklusjoner og kapittel 7 peker på videre arbeid som vil komplettere metodene og resultatene.

1.2. Definisjon av fremmedvann

Det finnes ulike definisjoner på fremmedvann. Fellessystem er oftest dimensjonert for å transportere bort mer vann enn bare spillvann. I et slikt system er derfor ikke alt overvann/drensvann/grunnvann som renner i avløpsrørene definert som fremmedvann. Separatsystemets spillvannsledning er oftest dimensjonert for bare å transportere bort spillvann. I et separatsystems spillvannsledning er det derfor vanlig å definere alt overvann som fremmedvann. I det arbeidet som er gjort i denne avhandlingen er fremmedvann definert som alt det vannet som kommer inn i avløpssystemets spillvannsledning som ikke er spillvann.

1.3. Konsekvenser av fremmedvann

Fremmedvann fører til en rekke uønskede konsekvenser. Fremmedvannet tar opp plass i avløpsrørene, gir økte driftsutgifter, økt vedlikeholdsbehov, kapasitetsproblemer i både ledningsnett og i avløpsrenseanlegg, noe som igjen fører til overløpsutslipp, samt økte restutslipp fra renseanlegg og mulig forringelse av resipienttilstand samt kjelleroversvømmelser [1-4]. Fremmedvann er i de fleste avløpssystemer ikke bærekraftig. Tradisjonell inndeling i bærekraft inkluderer et sosialt, miljømessig og økonomisk perspektiv [5]. Konsekvenser av fremmedvann i et bærekraftperspektiv illustreres i Figur 1.



Figur 1: Konsekvenser av fremmedvann i et bærekraftperspektiv, med et sosialt, miljømessig og økonomisk perspektiv

Mer kunnskap om både årsakene til at fremmedvann finner veien inn i avløpssystemene og mulige løsninger på de utfordringene fremmedvann fører til, kan derfor bidra til å redusere konsekvensene av fremmedvann og på den måten gjøre eksisterende avløpssystem mer bærekraftig.

Nettopp det miljømessige og sosiale perspektivet på fremmedvann er vanskelig å prissette. Tidligere utredninger som ser på konsekvenser av fremmedvann mangler derfor ofte konkrete tall på disse to perspektivene.

1.4. Økt fokus på fremmedvann

Norsk Vann er en interesseorganisasjon i Norge og en viktig aktør i den norske vann- og avløpsbransjen. Norsk Vann er også et viktig talerør inn i ulike debatter som til enhver tid preger vann- og avløpsbransjen.

Fra og med 2002 ble rapporteringsregimet «Bedre Vann» innført fra Norsk Vann [6]. Det første året ble det i avløpssammenheng og på ledningsnettsiden rapportert på parameterne; overløpsdrift, fornyelsestakt, antall kloakkstopper og antall kjelleroversvømmelser [7]. Rapporteringssystemet har endret seg over tid, for å ivareta de skiftene som oppstår i samfunnet. Fra og med 2018 rapporteres det fortsatt på de samme parameterne som i 2013, men i tillegg er det tatt inn en vurdering av bærekraftig andel fremmedvann. Kommunene skulle fra og med 2018 rapportere inn hvilke mål egen virksomhet har når det gjelder fremmedvannsandel, og også gjøre en beregning av hvor stor denne andelen er [8].

Norsk Vann utarbeidet i 2017 en egen bærekraftstrategi for vann- og avløpsbransjen. Strategien har til hensikt å bidra til det grønne skiftet og til å innfri FNs bærekraftsmål nr. 6, som omhandler forvaltning og tilgang til rent vann og gode sanitærforhold [9]. For å støtte opp under denne målsettingen har det blitt utarbeidet flere delmål. Delmål 4 omhandler ledningsnettets funksjonalitet, og delmål 4.2 omhandler fremmedvann. Målsettingen i strategien sier at flest mulig virksomheter skal utarbeide en plan for reduksjon av fremmedvann innen 2020, og at andelen for bransjen som helhet skal reduseres med 30% innen 2030 [9]. Økt fremmedvannsfokus gjenspeiles også på andre områder. I 2019 ble en doktorgrad med fokus på fremmedvann avsluttet ved NTNU (Norges teknisk-naturvitenskapelige universitet) i Trondheim. Arbeidet hadde blant annet fokus på bruk av DTS (Distributed Temperature Sensors) som metode for å lokalisere fremmedvann [10].

Også i de andre nordiske landene har det vært et økt fokus på fremmedvann de siste årene. I Gøteborg kommune i Sverige er det blant annet opprettet en industridoktorand stilling med fokus på fremmedvann. Det danske rapporteringssystemet «vand i tal», utarbeidet av DANVA (Dansk Vand- og Spildevandsforening), tok fra 2017 inn rapportering på fremmedvann [11].

De siste 20 årene (2001-2020) er det publisert en del artikler med fokus på fremmedvann. Tabell 1 viser resultatet av en gjennomgang av søkermotoren Google Scholar. Tabellen oppsummerer antall relevante, tilgjengelige, publiserte vitenskapelige artikler. I søket har «*Infiltration and Inflow*» vært eneste søkeord. Søket viser at det har vært en betydelig økning i antallet relevante og publiserte artikler innenfor temaet. I tillegg er relevante, fagfellevurderte artikler publisert i tidsskiftet VANN inkludert i tabellen.

Tabell 1: Antall relevante og publiserte vitenskapelige artikler med fokus på fremmedvann de siste 20 årene

År	**Antall**
2001-2005	3
2006-2010	6
2011-2015	14, hvorav 4 i VANN
2016-2020	19, hvorav 2 i VANN

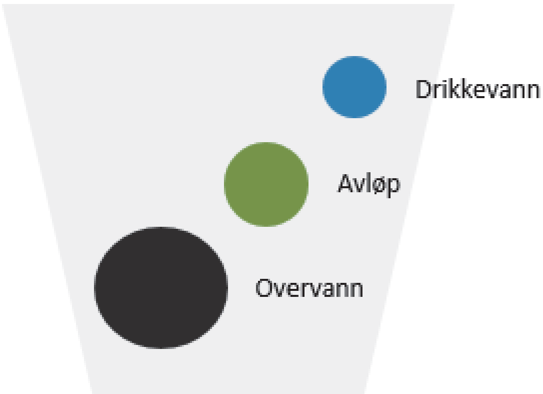
Oversikt over publiseringsår, forfattere og hvor artiklene er publisert vises i vedlegg 1.

En tredjedel av publisert materiale de siste 10 årene har nordiske forfattere. Som tidligere diskutert foregår det helt sikkert mye arbeid innenfor temaet fremmedvann som ikke er publisert i vitenskapelige artikler både i Norge og i resten av verden, men dette arbeidet er det vanskelig å få en oversikt over.

1.5. Årsaker til store forskjeller i fremmedvannsmengder

Norge har de største andelen fremmedvann av de Nordiske landene [12-14]. Beregnet gjennomsnittlig andel inn til noen av de største avløpsrenseanleggene i Norge var i 2016 på 66% [14]. Beregnet andel for Sverige for 2016 var på 46%, for Danmark på 30% og for Finland på 40% [14]. Variasjonene innenfor landene er store. Enkelte områder innenfor alle de undersøkte landene har adskillig både lavere og høyere andeler fremmedvann enn gjennomsnittsverdiene [14].

Utforming av grøftetverrsnitt for vann og avløp gjøres ulikt i ulike land. I Norge ser et vanlig grøftesnitt for et separatsystem ut som vist i Figur 2.



Figur 2: Typisk norsk grøftetversnitt [14]

En slik innbyrdes plassering vil sannsynligvis føre til at mye av grunnvannspåvirkningen skjer i overvannsrøret, men det vil avhenge av hvor høyt grunnvannsstanden står. Denne innbyrdes plasseringen vil også kunne føre til at avløpsledningene blir påvirket av lekkasjer fra drikkevannsnettet. Lekkasjeandelene fra drikkevannsledninger i Norge er høye, i 2017 var lekkasjetallet som et snitt for hele Norge på 30% [15]. Det er derfor naturlig å tro at dette kan være en faktor som kan bidra til de høye andelene fremmedvann i Norge. En annen faktor som kan påvirke andelene fremmedvann er sesongvariasjoner med snøsmelting. Tidligere undersøkelser med bruk av DTS har vist at smeltevann trenger inn i avløpsrørene andre steder enn regnvann [16]. Områder med mye snø og flere smelteperioder vil derfor kunne ha høyere andeler fremmedvann enn områder med mindre snø og mindre variasjoner. Temperaturer og sesongvariasjoner vil også kunne påvirke et forhold som minimums leggedybde på avløpsrørene. Rør som blir lagt i områder med telefare må legges dypere enn i områder uten telefare. Dette vil påvirke sannsynligheten for økt grunnvannsinntrengning. Andre faktorer som kan påvirke andeler fremmedvann er andel fellessystem [14] alder på ledningsnettet [17, 18] og nedbør [17, 19].

I resten av Europa vil et typisk grøftetverrsnitt, for et separatsystem, se ut som vist i Figur 3.

Figur 3: Typisk Europeisk grøftetverrsnitt

I land uten telefare vil rørene ligge grunnere enn det de gjør i de fleste nordiske land. Den innbyrdes plasseringen av rørene som vist i figur 3, burde tilsi ugunstigere forhold med hensyn på mengden fremmedvann enn det vi har det i Norge, hvor overvannsledningen er nederst i grøftene. Dette fordi jo dypere en ledning ligger desto mer grunnvann lekker inn. Videre må man ofte koble drensledninger fra bygningene til den nederste ledningen, som i andre land enn i Norge blir til spillvannsledningene.

Hvilke variabler som påvirker andelene fremmedvann vil variere fra sted til sted. Innbyrdes rangering av ulike påvirkningsfaktorer, for eksempel innenfor ulike avløpssoner, bør styre valg av tiltak. Hvordan dette kan gjøres demonstreres gjennom kapittel 3.4 i foreliggende arbeid.

1.6. Hvordan identifisere fremmedvann?

Identifisering av kilder til fremmedvann kan gjøres på mange ulike måter. Befaring under ulike værforhold vil kunne gi gode indikasjoner på hvilke områder som har inntrengning av fremmedvann. Rørinspeksjon kan også brukes til å identifisere fremmedvann, men dette vil kreve at inspeksjonen gjennomføres på det tidspunktet vannet finner en vei inn i røret.

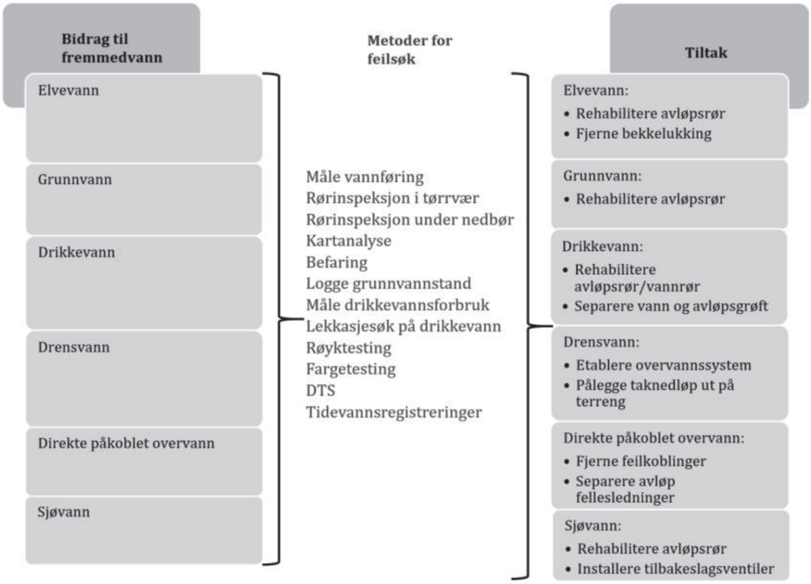
For mer kontinuerlige og målebaserte metoder kan for eksempel målinger av vannføring i avløpsrør benyttes. De enkleste og groveste metodene for å anslå fremmedvannsmender på er basert på vannbalanser inn og ut av avløpssystemet [3, 12, 13, 20-22]. Videre kan ulike sporstoff/naturlige tracere brukes til å identifisere vannveier [2, 3, 20, 23-26]. Av mer kvalitative metoder finner vi røyktesting, [3, 27] farging og DTS [3, 16, 28].

Det blir gjennom denne PhDen demonstrert hvordan data fra vannføringsmålere kan brukes til flere ulike analyser. Vannføringsmålinger kan være grunnpilaren i et systematisk arbeid mot fremmedvann.

1.7. Tiltak mot fremmedvann

Det finnes flere mulige tiltak som kan bidra til å redusere fremmedvannsmengdene [1, 29]. Tiltakene kan i hovedsak deles inn i fire kategorier; a) rehabiliteringstiltak b) omkoblingstiltak c) lokale overvannstiltak d) separeringstiltak. Med separeringstiltak kreves det i de fleste tilfeller at det legges ned nye overvannsledninger. I noen tilfeller vil omkoblingstiltak også kreve at det etableres nye overvannsledninger dersom dette ikke finnes fra før. I hvor stor grad lokale overvannstiltak bidrar til reduserte fremmedvannsmengder er usikkert. Jeg har ikke funnet noen studier som ser på sammenheng mellom lokale overvannstiltak og endringer i fremmedvannsmengder. I verste fall kan økende grad av lokale overvannstiltak føre til økende fremmedvannsmengder. Omkoblingstiltak er de tiltakene som med aller størst sannsynlighet vil bidra positivt på fremmedvannsmengdene.

Hvilke tiltak som bør iverksettes avhenger av hvor fremmedvannet kommer fra. Figur 4 illustrer hvilke vannkilder som kan bidra til fremmedvann, ulike metoder for feilsøk samt mulige tiltak mot fremmedvann.



Figur 4: Vannkilder, ulike metoder for feilsøk samt mulige tiltak mot fremmedvann

Uansett hvilke tiltak som benyttes bør alltid effekten undersøkes og dokumenteres. Dette er en vanskelig oppgave siden fremmedvannet i stor grad er styrt av nedbør, og som i liten grad har fått fokus i tidligere forskningsarbeid på fremmedvann.

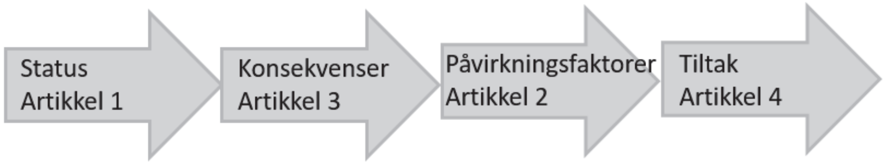
1.8. Hovedmålsetting og forskningsspørsmål

Klimaendringer, økte andeler ikke-permeable overflater, og befolkningsvekst er alle faktorer som potensielt kan påvirke fremmedvannsmengdene. [3, 14, 17, 30]. I tillegg er det en økende bevissthet i befolkningen rundt klima og miljøutfordringer, og dette er ikke forenelig med et ikke-funksjonelt avløpsnett. Økt kunnskap hos beslutningstakere om årsakssammenhenger og økt forståelse av konsekvenser og tiltak vil kunne bidra til å nå de nasjonale målene som er satt for en mer bærekraftig avløpsbransje.

Til tross for økt fokus på fremmedvann mangler en mer helhetlig tilnærming. Det er gjort mye arbeid som ser på deler av problematikken, og det finnes for eksempel mange gode studier som ser på hvordan fremmedvann kan lokaliseres. Etter mitt skjønn mangler rammeverket for totalen. I tillegg er det viktig å supplere og tilgjengeliggjøre de metodene som finnes slik at de enkelt kan tas i bruk av de som er satt til å forvalte vann- og avløpsinfrastrukturen.

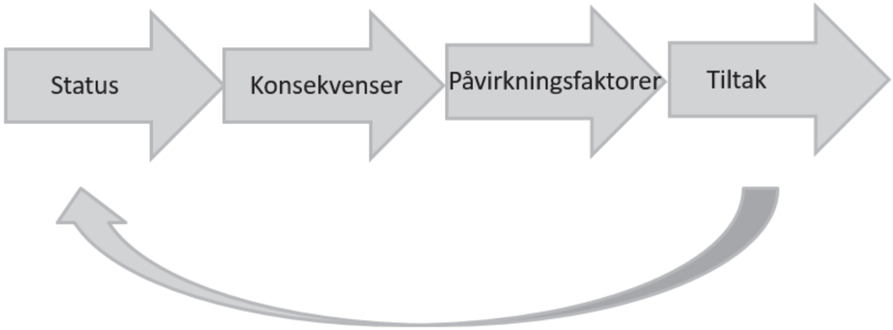
Hovedmålsetting med det arbeidet som er gjort er å øke kunnskapsnivået rundt fremmedvann. I tillegg skal arbeidet belyse ulike verktøy som kan brukes til å få en bedre forståelse for hva som påvirker fremmedvannsmengdene og hvilke mulige løsninger som finnes. De metodene som er benyttet er forholdsvis enkle og er verktøy som kommunene kan ta i bruk for å få bedre forståelse av fremmedvannets natur. Basis for alle undersøkelsene, bortsett fra multivariatanalysen i kapittel 3.4, er vannføringsmålinger ute på avløpsnettet. Vannføringsmålinger er grunnpilaren som må på plass for å kunne si noe om status, konsekvenser, påvirkningsfaktorer og effekt av tiltak.

Fremmedvann blir gjennom fire studier belyst fra ulike perspektiv. Hvordan studiene henger sammen vises i Figur 5.



Figur 5: Sammenheng mellom de fire studiene som er gjort gjennom PhD arbeidet

Arbeidsmetodikken som er benyttet kan brukes av andre kommuner som vil arbeide systematisk med fremmedvann. Et viktig prinsipp her er at effekten av de tiltakene som gjennomføres bør undersøkes. En konsekvens av tiltak kan være at status endres. Ved å legge til dette perspektivet ser den benyttede arbeidsmetodikken ut som vist i Figur 6.



Figur 6: Overordnet arbeidsmetodikk for systematisk arbeid med fremmedvann

Tabellene 2 -5 gir en oversikt over hensikt, forskningsspørsmål, data og metode i de ulike studiene som er gjennomført.

Tabell 2: Opplysninger om studie 1- Infiltration and Inflow (I/I) to Wastewater Systems in Norway, Sweden, Denmark and Finland

STATUS			
Hensikt	**Forsknings-spørsmål**	**Data**	**Metode**
Å undersøke utviklingen av fremmedvann. Hvilken effekt har tidligere tiltak hatt?	Hvordan har utvikling av fremmedvann vært i de nordiske landene de siste årene? Hvilke metoder kan brukes for å beregne fremmed-vannsmengder?	Tot-P inn til store RA i Norge. Vann-mengder inn til RA i Sverige, Danmark, Asker, Bærum og Solum-strand RA i Drammen	Fortynnings-metoden og vann-balanse-metoden

Tabell 3: Opplysninger om studie 2- Identifying factors influencing Infiltration and Inflow-water (I/I-water) in wastewater system using multivariate data analysis

PÅVIRKNINGSFAKTORER			
Hensikt	**Forsknings-spørsmål**	**Data**	**Metode**
Å undersøke om en multivariat analyseteknikk kan brukes til å undersøke påvirknings-faktorer på fremmed-vann. Å gjøre under-søkelser av i hvor stor grad lekkasjer fra vannlednings-nettet påvirker fremmed-vanns-mengdene	Er en multivariat-analyseteknikk en egnet metode for å undersøke påvirknings-faktorer på fremmedvann? Hvilke av de undersøkte faktorene påvirker fremmedvanns-mengdene i Norge?	Opplysninger om nedbør (eKlima), andel felles-system, andel fornyet avløpsnett, levert drikkevann, drikkevanns-lekkasjer, alder på avløpsrør (alle fra Kostra). Dessuten vannførings-data og lekkasje-data fra Asker kommune	Principal Component Analyse. Vannbalanse-metoder både på drikkevann og avløpsvann

Tabell 4: Opplysninger om studie 3- Analysing consequences of Infiltration and Inflow water (I/I-water) using Cost Benefit Analyses

KONSEKVENSER			
Hensikt	**Forsknings-spørsmål**	**Data**	**Metode**
Å tallfest konsekvensene av fremmedvann økonomisk samt gjøre en samfunns-økonomisk analyse av tiltak mot fremmed-vann. Å undersøke hvor stor betalings-villigheten i befolkningen er for å få en bedring i vannkvalitet.	Hva koster fremmedvann? Hvilke tiltak er de mest samfunns-økonomiske mot fremmedvann?	Utslipps-regnskap fra Asker kommune samt VEAS. Data fra pumpedrift i Asker og fra års-rapporter fra VEAS. Ulik litteratur ang betalings-villighet	Samfunns-økonomisk analyse med nåverdi-metoden. I tillegg Beregninger av overløpsutslipp med hydraulisk modell. Litteraturstudie ang betalings-villighet for bedring i vann-kvalitet

Tabell 5: Opplysninger om studie 4- What effect does traditional rehabilitation of wastewater pipelines have on the share of Infiltration and Inflow water (I/I-water)?

TILTAK			
Hensikt	**Forsknings-spørsmål**	**Data**	**Metode**
Å finne en metode for å dokumentere effekt av ulike tiltak på avløpsnettet. Å undersøke hvor stor effekt tradisjonelle rehabiliterings-tiltak har på fremmed-vanns-mengdene	Hvilken metode er egnet til å dokumentere effekt av tiltak mot fremmedvann? Hvor mye fremmedvann kan fjernes med tradisjonelle rehabiliterings-tiltak?	Lednings-nettdata fra Asker kommune. Målinger av vannføring og overløpsdrift ulike steder i Asker.	Vannbalanse-metoden.

2. Forskningstilnærming

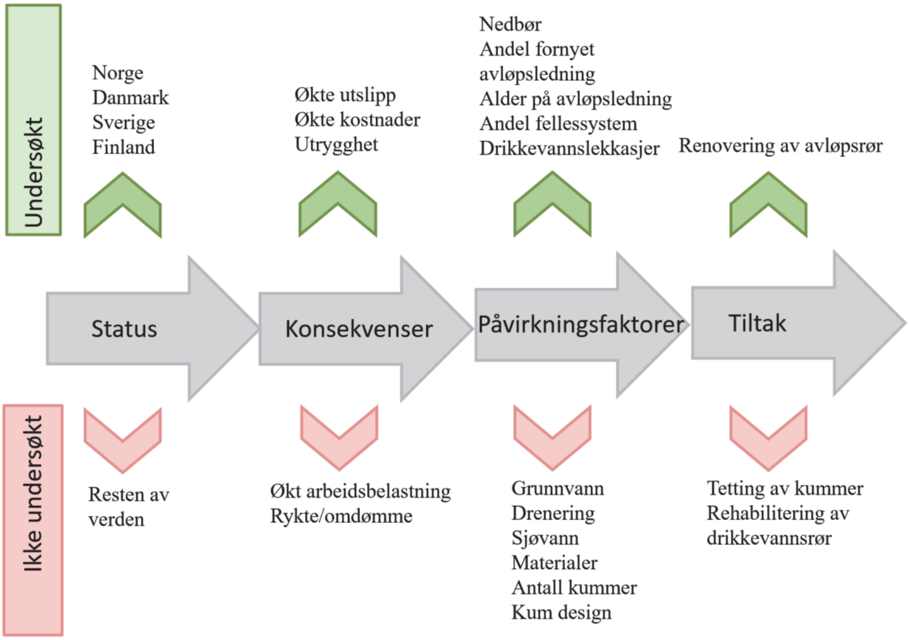
Siden det har blitt jobbet systematisk med fremmedvann mange steder over flere år er det interessant å se på om arbeidet har gitt resultater. Dette er utgangspunktet for den første delen av denne avhandlingen. Den første artikkelen belyser utvikling av fremmedvannsmengder i Norge, Sverige, Danmark og Finland. I de beregningene som er gjort er det hentet ut data fra offentlige tilgjengelige datakilder. Beregning av fremmedvann kan gjøres på flere måter, men gjennom denne avhandlingen trekkes særlig fortynningsmetoden og vannbalansemetoden frem [14]. Andre aktuelle metoder for å kvantifisere fremmedvannsmengder er basert på minimum natt-tilrenning og sporingsmetoder [3]. De sistnevnte metodene er i utgangspunktet basert på de samme antakelsene som både vannbalansemetoden og fortynningsmetoden, nemlig at hver PE (Person Ekvivalent) produserer en viss mengde avløpsvann i løpet av et døgn, og at fremmedvann vil føre til fortynning av et valgt sporstoff. I vannbalansebetraktninger er viktige input antall PE innenfor det aktuelle tilrenningsområdet, sammen med kunnskap om drikkevannsforbruk innenfor det samme området. Når det gjelder fortynning/sporingsmetoder er det viktig å vite noe om hvilke konsentrasjoner en kan forvente å finne av det aktuelle stoffet i et upåvirket avløpssystem. I det tilfellet hvor fosfor brukes som sporingsstoff vil opplysninger om fosforproduksjon per PE/døgn være viktige.

Hvor store fremmedvannsmengder som tilføres avløpssystemet påvirkes av flere ulike faktorer. Artikkel 2 i denne avhandlingen ser på i hvilken grad en multivariat analyseteknikk er en egnet metodikk for å undersøke påvirkningsfaktorer på fremmedvannet. Som case brukes de største avløpsrenseanleggene i Norge. Også i artikkel 2 er det hentet ut data fra offentlige tilgjengelige datakilder. Det er analysert på andel lekkasjer fra drikkevann, mengde levert drikkevann, gjennomsnittsalder på avløpsledninger, andel fornyet avløpsledning, andel fellessystem og nedbør. I tillegg er det gjort en undersøkelse av bidrag fra drikkevannslekkasjer. I andre europeiske land trekkes grunnvann frem som en vesentlig faktor når det gjelder andel fremmedvann [18, 31]. Det er ikke tradisjon for å måle grunnvannsnivå i Norge. I hvilken grad grunnvann er en vesentlig faktor for høyt fremmedvannsnivå i Norge er derfor usikkert og ikke undersøkt spesielt. I tillegg er det gjort undersøkelser for ulike avløpsfelt i Asker når det gjelder sammenhenger mellom drikkevannslekkasjer og fremmedvannsmengder.

I artikkel nummer 3 er det sett på hvilke konsekvenser et dårlig fungerende avløpsnett kan føre til. Det er gjort beregninger av de økonomiske konsekvensene av fremmedvann. Fremmedvann fører blant annet til overløpsutslipp, så en vesentlig del av dette arbeidet omhandler prissetting av forurensningsutslipp. Fosfor er brukt som indikator. Forurensningsregnskap for Asker kommune sammen med utslippsrapporter fra VEAS (Vestfjorden Avløpsrenseanlegg) danner bakgrunnen for noen av de beregningene som er gjort. I tillegg er det gjort en kost-nytte-analyse av utvalgte tiltak. Inkludert i beregningene er en vurdering av betalingsvillighet for bedring i vannkvalitet og unngåtte kjelleroversvømmelser.

I den fjerde og siste artikkelen er ulike rehabiliteringsområder i Asker brukt som caseområder. Det er i disse områdene gjort målinger av vannføring og overløp både før og etter gjennomføring av flere ulike tiltak. Siden fremmedvannsmengdene i stor grad er avhengig av nedbør er det vanskelig å finne helt sammenliknbare måleperioder før og etter gjennomført tiltak. For å komme rundt akkurat denne utfordringen er det innført kontrollområder. Det betyr at det er gjort målinger av vannføring og overløp også i soner hvor det ikke er gjennomført tiltak. Denne metoden er velkjent i uttesting av for eksempel nye medisiner, og er også tidligere testet på tiltak mot fremmedvann [32]. Hensikten med den 4. delen av arbeidet er å undersøke hvorvidt innføring av kontroll- områder er hensiktsmessig for å dokumentere effekt av tiltak, og å undersøke hvilken effekt tradisjonelle rehabiliteringstiltak gir på fremmedvannsmengdene.

Hvilke avgrensninger som er gjort gjennom PhD- arbeidet er illustrert i Figur 7.



Figur 7: Avgrensinger av arbeidet som er gjort

3. Metoder

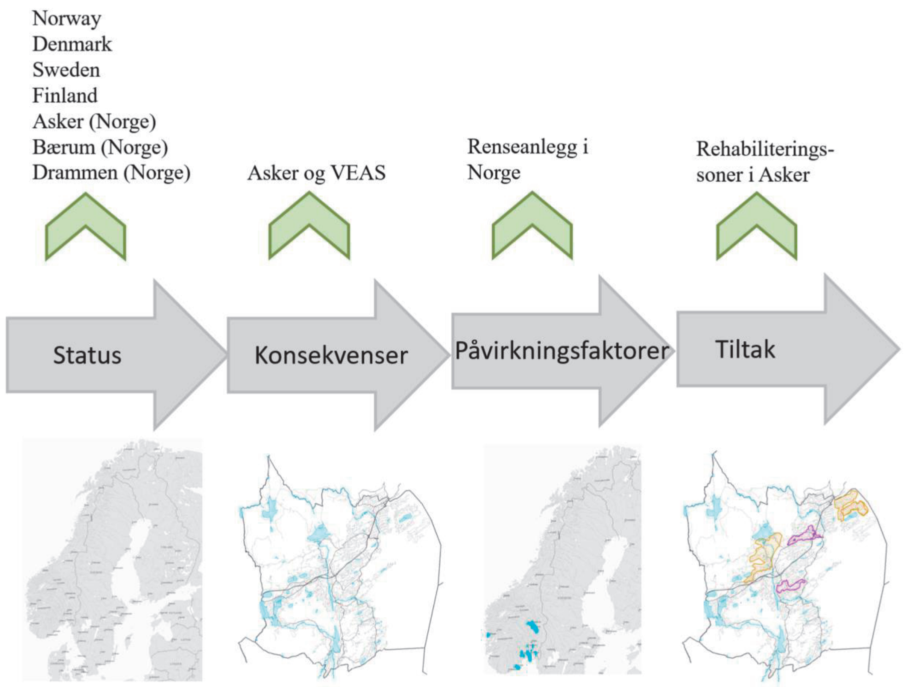
3.1. Studieområder

Studiene henter i hovedsak tall fra norske avløpsrenseanlegg og norske kommuner. I tillegg er det hentet tall fra Asker kommune i Norge til flere av de undersøkelsene som er gjort. Fra 01.01.2020 ble Asker kommune slått sammen med tidligere Hurum og Røyken kommuner. Undersøkelsene er gjort på data fra gamle Asker kommune.

Store deler av avløpsnettet i Asker ble bygget ut på 1960 og 1970-tallet, og består i stor grad av gamle betongrør. Asker har et 100%

separatsystem, men har til tross for dette store mengder fremmedvann. Spillvannsnettet fungerer derfor i praksis som et fellessystem med regnvannsoverløp. Alt avløpsvannet fra offentlig avløpsnett blir i gamle Asker kommune transportert til avløpsrenseanlegget VEAS. Det er ca.70 avløpspumpestasjoner i Asker og i tillegg ca. 30 overløp på ledningsnettet. Avløpsnettet består av 330 km med spillvannsledninger og 75 km med overvannsledninger Kommunen hadde i 2019 ca. 61000 innbyggere. Kommunen består i hovedsak av boligområder, men har også noen mindre sentrumskjerner og noen rene næringsområder.

Hvilke studieområder som er benyttet i de ulike artiklene vises i Figur 8 [33, 34].



Figur 8: Studieområder benyttet i de ulike arbeidene

I studie 1 er Norge, Sverige, Danmark og Finland brukt som studieområde. I tillegg er det gjort undersøkelser basert på tall fra tre kommuner i Norge; Asker, Bærum og Drammen. Undersøkelsen om konsekvenser henter bare tall fra Asker kommune samt VEAS. I studien om påvirkningsfaktorer er det gjort undersøkelser på de størst avløpsrenseanleggene i Norge, i tillegg til at det er brukt data fra Asker kommune på undersøkelser av hvordan drikkevannslekkasjer påvirker fremmedvannsnivået. Tabell 6 viser hvilke anlegg som er brukt i denne artikkelen.

Tabell 6: Anlegg benyttet i statistiske analyser i artikkel nummer 2

Avløpsrense-anlegg	**Tilknyttede kommuner**	**Måler nr.**	**Nedbørsmåler navn**
Kambo (Ka)	Moss	17251	Moss brannstasjon
Alvim (Al)	Sarpsborg	3190	Sarpsborg
Solumstrand (So)	Drammen	26900	Berskog
Sandefjord (Sf)	Sandefjord	27600	Sandefjord
Knardalstrand (Kr)	Porsgrunn, Skien	27600	Sandefjord
Saulekilen (Sau)	Arendal	36200	Torungen fyr
Knappen (Kn)	Bergen	50540	Florida
Lillehammer (L)	Lillehammer	12680	Sætherengen
Tønsberg (Tøn)	Tønsberg, Nøtterøy, Tjøme, Re, Stokke	27270	Kilen
HIAS (Hi)	Hamar, Løten, Ringsaker, Stange	12320	Stavsberg
Nordre Follo (NoF)	Ski, Ås, Oppegård	17850	Ås

I studie fire er det brukt data fra fem ulike avløps- målesoner i Asker.

Fremmedvann ble i hovedplanen til Asker kommune (2018) definert som en av de største utfordringene på avløpssiden. Dette er bakgrunnen for valg av tema for det arbeidet som er gjort gjennom denne PhDen. Andelen fremmedvann lå i 2017 på 60% av det totale volumet som ble transportert til VEAS

3.2. Bruk av vannføringsmålinger

Data fra vannføringsmålere er brukt i tre av fire undersøkelser. Disse vannføringsmålerne er mobile målere som monteres direkte inn i eksisterende avløpsnett.

Data fra installerte vannføringsmålere på avløpsnettet kan brukes til flere ting. Slike data kan blant annet brukes til å kalibrere hydrauliske nettmodeller, de kan brukes til å fange opp driftsforstyrrelser og til å få en oversikt over både innlekking og utlekking. Vannføringen måles ikke direkte, men beregnes ut fra målte verdier på hastighet og nivå, ved kjent tverrsnitt på røret. Ved lavere vannføringer enn ca. 2 l/s eller avrenningsområder med færre PE enn ca. 1000 kan det med dagens måleutstyr være krevende å få til gode målinger [35]. Men for områder med en minstevannføring på 2 l/s, og hvor måleforholdene er gode, kan vannføringsdata brukes til blant annet å beregne fremmedvannsmengdene i avløpssonene. Gode måleforhold betyr rolige strømningsforhold, rette strekninger der hvor måleren er plassert, samt at det ikke kommer vann fra grenrør direkte inn i vannstrømmen som skal måles [35].

3.3. Beregninger av fremmedvannsmengder (artikkel 1 - Status)

Dersom vannmengder skal brukes til å beregne andeler fremmedvann er det viktig å ha oversikt over vannforbruk. Målt drikkevannsforbruk trukket fra målte avløpsmengder gir andel fremmedvann. Drikkevannsforbruket vil variere mye over døgnet og over året, men med overslagsberegninger er det mulig å bruke slike data til å beregne andel fremmedvann. Vannbalansemetoden, som nettopp bruker vannføringsdata og forbruksdata for drikkevann, er brukt i artikkel 1 og 4. I artikkel 1 er det for kommunene Asker, Bærum og Drammen (Solumstrand rensedistrikt) gjort en vannbalanseberegning hvor totale avløpsmengder, antall tilknyttede personer og et stipulert vannforbruk er brukt. Denne metoden er også benyttet for å beregne fremmedvannsandel for noen danske, finske og svenske avløpsrenseanlegg. Beregninger med vannbalansemetoden gjøres etter formel 1 [12, 14].

Andel fremmedvann [%] = $(Q_{tot} - PE \times Q_{ap}) / Q_{tot}) \times 100$ (1)

Hvor:

Q_{tot} = totale mengder avløpsvann som kommer frem til målepunktet [*l*/dag]

PE = antall personer som er registrert innenfor målesonen

Q_{ap} = de avløpsmengdene hver person produserer hver dag [*l*/PE dag]

En annen metode som kan brukes til å beregne fremmedvannsandeler er «fortynningsmetoden». Fortynningsmetoden baseres på antakelsen om at hver person produserer en viss mengde sporstoff hver dag, for eksempel total-fosfor (ToT-P). Dersom en høy konsentrasjon av ToT-P kan måles i for eksempel innløpet til avløpsrenseanlegget, betyr det at det er en lav andel fremmedvann i det samme vannet. Jo mer uttynnet avløpsvannet er desto lavere vil andel av Tot-P være i det samme avløpsvannet. Hvordan andel fremmedvann kan beregnes med fortynningsmetoden vises i formel 2 [12, 14].

$$\text{Andel fremmedvann } [\%] = (1 - (c_i)/(P_{pd}/ Q_{ap})) \times 100 \qquad (2)$$

Hvor:

P_{pd} = produserte mengder total fosfor (Tot-P) per person og dag [mg/PE dag]

c_i = konsentrasjon av ToT-P inn på renseanlegget [mg/*l*]

Q_{ap} = de avløpsmengdene hver person produserer hver dag [*l*/PE dag]

Dersom fortynningsmetoden skal brukes må en anta en viss fosforproduksjon pr PE og døgn, i tillegg til å anta et visst vannforbruk pr PE og døgn.

Begge de brukte metodene har svakheter. Dersom det er usikkerheter knyttet til enten drikkevannsforbruk, målte avløpsmengder eller fosforproduksjon vil dette påvirke påliteligheten til resultatene. I tillegg kan inn- og utpendling i målesonene potensielt spille en stor rolle. Det samme gjelder industriforbruk/-utslipp. Dersom vannbalansemetoden skal brukes bør en også ha oversikt over hvor mye vann som forsvinner ut av systemet, for eksempel via overløp. For små områder er det lettere å ha kontroll på de viktigste usikkerhetsfaktorene enn i store og mer uoversiktlige områder. I de beregningene som er gjort av fremmedvannsandeler er det hentet ut data fra områder av ulik størrelse. Kvaliteten på resultatene er derfor variabel.

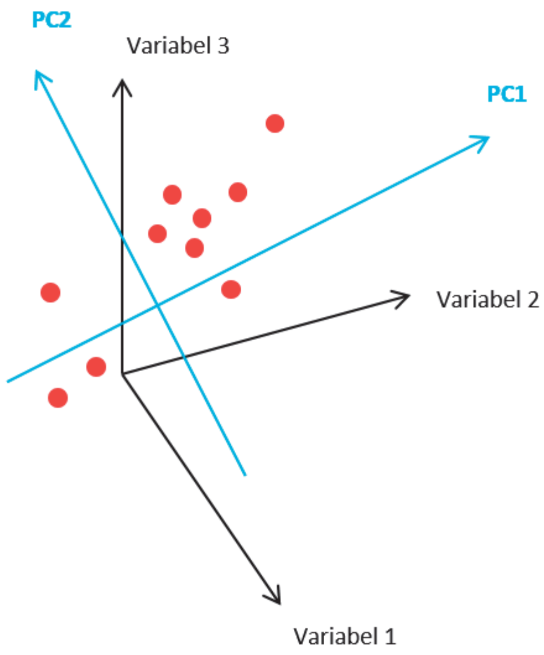
3.4. Statistiske analyser (artikkel 2 - Påvirkningsfaktorer)

3.4.1. Lineær regresjon

Gjennom studie to er det gjort en lineær regresjon for å undersøke ulike variabler som muligens kan påvirke fremmedvannsmengdene. De variablene som har blitt korrelert mot verdier på ToT-P er: a) vannlekkasjer fra drikkevannsledninger, b) leverte mengder drikkevann fra vannbehandlingsanlegg, c) gjennomsnittsalder på ledningsnettet, d) andel fornyet avløpsledningsnett, e) andel fellessystem og f) nedbør. Variablene har blitt sjekket mot andeler ToT-P, en og en. I regresjonsanalysen har et 98% konfidensintervall blitt brukt.

3.4.2. Multivariat analyse

Ved å ta i bruk en statistisk metode som multivariat analyse, kan flere variabler undersøkes samtidig. Med en sånn metode vil det være mulig å undersøke hvorvidt det finnes mønstre som det er vanskelig å se med enklere statistiske analyser. I analysene i studie to er softwaren Unscrambler 10.5 blitt brukt. En Principal Component Analyse (PCA) er en type multivariat analyse. Ved å gjøre en Principal Component Analyse har det vært mulig å finne skjulte mønstre i datasett som ellers ville vært vanskelig å oppdage [17, 36]. Når det finnes skjulte mønstre i datasettene som undersøkes gjør PCA en dimensjonal reduksjon av ukorrelerte latente variabler. Nye PCer (Principal Componenter) vil til sammen forklare hvilke sammenhenger som finnes i datasettet som undersøkes [17, 36]. Hvordan ekstrakteringsprosessen av Principal Componenter gjøres vises i Figur 9.



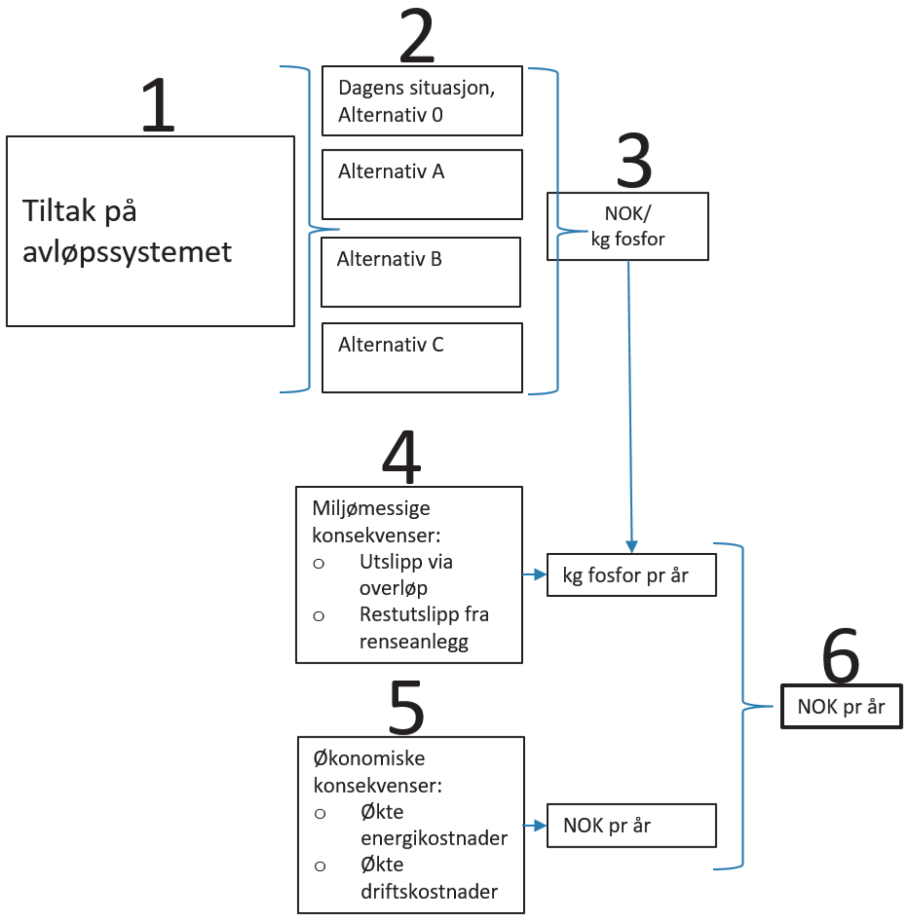
Figur 9: Ekstrakteringsprosess av PCer i en PCA [17, 37]

3.5. Samfunnsøkonomiske analyser (artikkel 3 - Konsekvenser)

Samfunnsøkonomiske analyser kan blant annet brukes til å vurdere kostnader og nytter av ulike tiltak. Det finnes ulike typer samfunnsøkonomiske analyser, som alle kan benyttes som beslutningsstøtte når det skal tas avgjørelser i offentlig sektor; kost-nytte analyser, kostnadsvirkningsanalyser og kostnadseffektivitetsanalyser [38]. I samfunnsøkonomiske analyser vurderes ulike tiltaks- alternativer opp mot et alternativ 0, hvor 0- alternativet innebærer å utføre bare et minimum av tiltak. Hensikten med en samfunnsøkonomisk analyse er å finne det mest økonomisk lønnsomme tiltaket [1, 38].

Gjennom studien om prissetting av fremmedvann har det blitt gjort en analyse av ulike tiltak mot konsekvensene av fremmedvann, hvor tiltakene er vurdert og rangert ut fra et samfunnsøkonomisk perspektiv. I tillegg til økte driftskostnader kan fremmedvann føre til kjelleroversvømmelser og overløpsutslipp, samt økte restutslipp fra renseanlegg. I en samfunnsøkonomisk analyse av tiltak mot konsekvenser av fremmedvann er det derfor viktig å prissette hva utslipp forårsaket av fremmedvann koster. Utslipp av kloakk inneholder mange uønskede stoffer. For eksempel kan utslipp av næringsstoffer føre til eutrofiering mens utslipp av bakterier og virus kan forårsake sykdom. Mange ulike indikatorer kunne altså vært brukt i en analyse av konsekvenser av fremmedvann, men det er gjennom studien valgt å se på indikatoren fosfor.

Prissetting av utslipp kan blant annet gjøres gjennom å sette en pris på hva det vil koste å fjerne utslippet, altså ved bruk av en såkalt tiltakskostmetode. Det er satt en pris på hva det vil koste å fjerne/redusere utslipp forårsaket av fremmedvann, og så er denne prisen brukt som et tall på hva det koster å slippe ut fosfor på grunn av fremmedvann. I stedet for å prise hva selve utslippet koster prissetter vi altså hva det til koste med tiltak for å forhindre selve utslippet. I tillegg må pris på kjelleroversvømmelser forårsaket av fremmedvann inkluderes. Tapt omdømme, for eksempel på grunn av overløpsutslipp og kjelleroversvømmelser, vil også kunne være en del av en slik samfunnsøkonomisk analyse, men er ikke inkludert i foreliggende arbeid. Figur 10 viser arbeidsmetodikk for hvordan en kan prissette fremmedvann.



Figur 10: Arbeidsmetodikk for prissetting av fremmedvann [1]

I steg 1 identifiseres mulige tiltak på avløpssystemet for å hindre konsekvenser av fremmedvann.

I steg 2 beregnes investeringskostnadene for de alternativene som er identifisert i steg 1.

I steg 3 beregnes fosforutslippene for alle alternativer

I steg 4 kvantifisere utslippsmengder på grunnlag av

fremmedvannsmengdene.
I steg 5 kvantifiseres direkte økonomiske konsekvenser som følge av fremmedvann.
I steg 6 bregnes utslippskostnader og de totale kostnadene for fremmedvann.

I alle typer samfunnsøkonomiske analyser kan betalingsvillighet brukes som et mål på hva nytteverdien av et tiltak er verdt i befolkningen [39]. Miljøgoder er offentlige goder og skal i prinsippet være tilgjengelig for alle [1, 39]. Slike goder kan ikke prises direkte i markeder men må prissettes uten markedspriser. En måte å prissette miljøgoder på er gjennom studier av betalingsvillighet [1, 40]. Siden utslipp av avløpsvann kan føre til eutrofiering og forringelse av vannkvalitet kan verdien av god vannkvalitet brukes som en nytteverdi. Denne verdien er gjennom foreliggende arbeid funnet gjennom litteraturstudier av tidligere gjennomførte undersøkelser av betalingsvillighet. God vannkvalitet kan verdsettes gjennom ulike økosystemtjenester. Gode fiskeforhold, god badevannskvalitet og vann egnet til jordbruksvanning er eksempler på økosystem- tjenester hvor vannkvaliteten spiller en avgjørende rolle.

Flere tiltak vil kunne redusere konsekvensene av fremmedvann. Noen tiltak kan utføres lokalt, det vil si enten på ledningsnett eller i tilknytning til overløpspunkt på avløpsnettet, eller tiltakene kan gjennomføres sentralt- altså i tilknytning til avløpsrenseanlegg.

Tiltakene kan også utføres enkeltvis eller i kombinasjon. Mulige tiltak er summert opp i Tabell 7.

Tabell 7: Mulige tiltak for å redusere konsekvenser av fremmedvann

		Påvirkning resipient
Lokale tiltak	Rehabilitering av ledninger/kummer Søk etter feilkoblinger Oppdimensjonering av lokale flaskehalser Fordrøyning	Lokal og sentral Lokal og sentral Lokal Lokal
Sentrale tiltak	Utvidelse av renseanlegg Fordrøyning	Sentral Sentral

De alternativene som har blitt vurdert gjennom artikkel 3 er; a) renovering av alle antatt dårlige avløpsrør i kombinasjon med søking etter feilkoblet overvann, b) oppdimensjonering av lokale flaskehalser samt etablering av fordrøyningsbasseng ved VEAS, c) etablering av fordrøyning lokalt og ved VEAS.
To viktige forutsetninger som er lagt til grunn i alternativ a) er at andelen fremmedvann som blir fjernet med tiltaket er 50%, og at vi må renovere 20% av ledningsnettet for å oppnå denne effekten. De 20%ene er satt på bakgrunn av gjennomførte rørinspeksjoner av ledningsnettet i Asker.

Når det er satt en pris på utslipp forårsaket av fremmedvann er det også mulig å sette en total pris på hva fremmedvann koster. Fremmedvannskostnadene beregnes etter formel 3.

$$Tot\ Kost_{fr} = D\ Kost_{fr} + U\ Kost_{fr} \qquad (3)$$

Hvor:

$Tot\ Kost_{fr}$ = De totale kostnad for fremmedvann (kroner/år)

$D\ Kost_{fr}$ = fremmedvannsrelaterte driftskostander (kroner/år)

$U\ Kost_{fr}$ = fremmedvannsrelaterte utslippskostnader (kroner/år)

3.6. Bærekraftig andel fremmedvann

I hvilken grad fremmedvannet bør reduseres vil avhenge av i hvor stor grad fremmedvannet fører til uønskede konsekvenser. I et system med høy andel fremmedvann, men hvor fremmedvannet likevel ikke fører til uønskede konsekvenser, bør antakelig vann- og avløpsressursene brukes på andre tiltak enn på de som har som mål å fjerne fremmedvann. Særlig gjelder dette i områder hvor reint vann ikke er en begrenset ressurs. Før tiltak iverksettes bør det altså være klart a) hvilke føringer som styrer tiltakene b) hvilke tiltak som er det mest kostnadseffektive for å oppnå ønsket effekt.

Det er i foreliggende arbeid ikke inkludert sårbarhetsvurderinger i resipient. Dersom en slik vurdering hadde vært inkludert ville resultatene gitt et mer nyansert bilde. For eksempel vil den resipienten som mottar utslippene fra renseanlegget ofte være mer robust, med høy tåleevne, enn en mindre, mer sårbar, lokal resipient. Dersom en høy andel fremmedvann, og dertil høye overløpsutslipp, ikke medfører negative konsekvenser, vil det sannsynligvis ikke være bærekraftig å investere store summer for å redusere fremmedvannsmengdene. Investeringskostnadene bør altså balanseres opp mot konsekvensene.

3.7. Effekt av ulike tiltak (artikkel 4 - Tiltak)

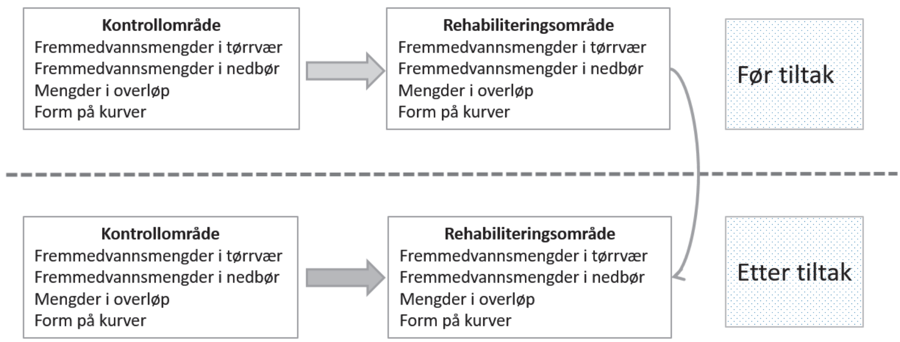
Rehabilitering av avløpsledninger er en vanlig metode for å redusere fremmedvann. Den enkleste og billigste måten å rehabilitere på er å strømperehabilitere ledningene. Ved strømperehabilitering tettes hele eller deler av ledningen. En mulig måte å jobbe på er å utføre tiltak etter hvor feil er lokalisert, for eksempel gjennom feilidentifikasjon ved bruk av rørinspeksjon. Tiltak i kummer vil variere fra ingenting til full utskiftning.

Uansett tiltak er det viktig å kunne måle effekten av tiltak som gjennomføres. Vannføringsdata er en vanlig måte å dokumentere hvor mye vann som renner gjennom for eksempel avløpsledninger. En utfordring med å bruke vannføringsmålinger til å dokumentere effekt av tiltak på avløpsledninger, for eksempel målt som redusert andel fremmedvann, er at det er vanskelig å finne to helt like nedbørsituasjoner før og etter tiltak. Selve nedbørsituasjonen kan det finnes like av, men avrenningen til avløpsrørene vil påvirkes også av nedbør i forkant av selve hendelsen, av temperatur og snøsmelting. Med bakgrunn i klimatiske forhold er det derfor vanskelig å bruke vannføringsmålinger til å dokumentere effekt av tiltak mot fremmedvann[35] . For å komme rundt denne utfordringen er det gjennom studie fire testet ut bruk av «kontrollområder». Bruk av kontrollgrupper er velkjent fra blant annet forskning innenfor medisin og har også blitt utprøvd tidligere på tiltak på avløpsnett [32, 35]. I tillegg til å bruke vannføringsdata er det også sett på overløpsregistreringer, både i et kontrollområde og i et rehabiliteringsområde. Overløpsdrift er i undersøkelsen logget med målere som består av to elektrode-sensorer. Hver gang vannet stiger over sensorene vil salter i vannet føret til at det blir kontakt mellom elektrodene. Slike hendelser blir registrert som overløp [35].

I undersøkelsen er det hentet ut data fra 3 ulike rehabiliteringsområder og fra 2 kontrollområder.

- Rehabiliteringsområdene Dæli og Vakås har kontrollområde J.R.Wilhelmsens vei (JRWs vei)
- Rehabiliteringsområdet Vestre vei har kontrollområde Holmen

Metodikken som er brukt for å undersøke effekt av rehabiliteringstiltak vises i Figur 11.



Figur 11: Metodikk for å undersøke effekt av tiltak på avløpsnettet [35]

Karakteristika for de vurderte områdene vises i Tabell 8.

Tabell 8: Karakteristika for vurderte rehabiliteringsområder

Område	Total lengde spillvanns-ledning (m)	Total lengde drikkevanns-ledning (m)	Antall PE
Dæli	12000	10500	3000
Vakås	9500	11300	2000
Vestre vei	15000	11300	3000

Gjennomførte tiltak på avløpsledninger og drikkevannsledninger vises i Tabell 9.

Tabell 9: Oppsummering av gjennomførte tiltak på avløpsledninger

Område	Rehabilitert lengde spillvanns-ledning (m)	%	Rehabilitert lengde drikkevanns-ledning (m)	%
Dæli	1500	13	300	3
Vakås	1000	11	1300	12
Vestre vei	1000	7	0	0

Gjennomførte tiltak på avløpskummer vises i Tabell 10.

Tabell 10: Oppsummering av gjennomførte tiltak på avløpskummer

Område	Antall rehabiliterte spillvanns-kummer	% rehabiliterte spillvanns-kummer
Dæli	27	12
Vakås	18	13
Vestre vei	24	10

Det er i hovedsak gjennomført strømperehabilitering av gamle avløpsledninger i områdene Vestre vei og Dæli. I Vakås har metodikken vært oppgraving. Kummer har blitt rehabilitert der hvor det har blitt vurdert at dette er nødvendig etter inspeksjon. Det har ikke blitt leitet spesielt etter feilkoblinger, men der hvor det har blitt oppdaget feilkoblinger i forbindelse med rørinspeksjon eller anleggsarbeider har dette blitt utbedret. I Vakås- området krysser avløpsledningene en bekk på flere steder.

4. Resultater

4.1. Utvikling av fremmedvann (artikkel 1 - Status)

Utviklingen av andel fremmedvann inn til norske avløpsrenseanlegg har vært positiv fra 2008 til 2016. Fremmedvannsmengdene har gått ned for 11 av 15 anlegg til tross for økende nedbørsmengder [14]. For alle de undersøkte anleggene har andelen som en gjennomsnittsverdi blitt redusert fra 70% til 66% [14]. For kommunene Asker og Bærum har andel fremmedvann blitt redusert fra 71% til 63% og fra 77% til 64% [14]. For Solumstrand rensedistrikt i Drammen har andel fremmedvann økt. Beregninger med både vannbalansemetoden og med fortynningsmetoden for Solumstrand gir noe ulikt resultat. Beregninger gjort med disse to metodene er derfor ikke uten videre sammenliknbare. Vannbalansemetoden viser en økning fra 56% til 67%, fortynningsmetoden gir en økning fra 73% til 76% [14]. De undersøkte anleggene i Danmark viser et stabilt fremmedvannsnivå med 29% i 2010 og 30% i 2016 [14]. Undersøkte finske anlegg viser også et stabilt nivå på ca. 40%, mens det i Sverige har vært en positiv utvikling fra 58% i 2010 til 46% i 2015 [14]. Trenden for de fleste store avløspsrenseanleggene i Norge er altså positiv, til tross for at nedbørsmengdene har økt. Det samme kan også sies om fremmedvannsmengdene inn til store anlegg Sverige.

4.2. Påvirkningsfaktorer på fremmedvann (artikkel 2 - Påvirkningsfaktorer)

Konsentrasjonen av fosfor (ToT-P) i innløpet til avløpsrenseanleggene kan ved hjelp av fortynningsmetoden brukes til å undersøke andeler fremmedvann. Jo lavere ToT-P jo høyere andeler fremmedvann. Ved hjelp regresjonsanalyse er de utvalgte variablene; a) vannlekkasjer fra drikkevannsledninger, b) leverte mengder drikkevann, c) gjennomsnittsalder på ledningsnettet, d) andel fornyet avløpsledningsnett, og e) nedbør undersøkt mot ToT-P. Andel fellessystem er ikke inkluder i regresjonsanalysen fordi det pr 2016 ikke var innrapportert data på denne variabelen fra norske kommuner til tilsynsmyndighetene lenger enn fra 2013. Av 11 undersøkte RA er det muligens en sammenheng mellom Tot-P og enkelte variable for fire anlegg [17]. Resultatene fra regresjonsanalysen vises i

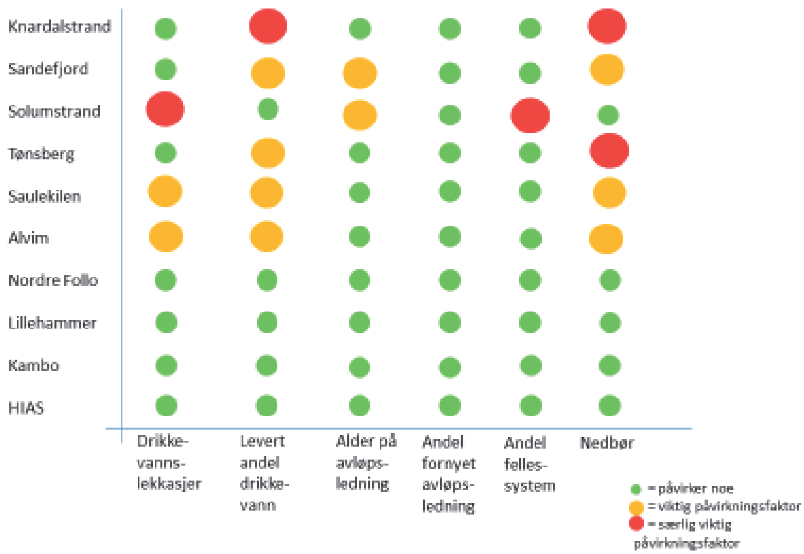
Tabell 11. Grønne verdier viser hvilke variabler som antakelig har en sammenheng med fremmedvannsnivået.

Tabell 11: Resultater fra regresjonsanalyse [17]

	Vann-lekkasjer		**Levert drikke-vann**		**Nedbør**		**Alder på avløps-ledninger**		**Fornyelses takt avløps-ledninger**	
RA	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
Kambo	0,13	0,34	0,03	0,65	0,11	0,36	0,15	0,29	0,01	0,80
Alvim	0,39	0,07	0,06	0,54	0,01	0,77	0,03	0,68	0,08	0,45
Solum-strand	0,00	0,89	0,14	0,32	0,06	0,51	0,00	0,91	0,08	0,47
Sandefjord	0,09	0,43	0,05	0,54	0,42	0,06	0,04	0,59	0,11	0,34
Knardal-strand	0,01	0,84	0,002	0,90	0,25	0,17	0,29	0,13	0,20	0,23
Saulekilen	0,08	0,47	0,06	0,54	0,12	0,36	0,08	0,46	0,33	0,10
Knappen	0,34	0,10	0,28	0,14	0,04	0,63	0,00	0,96	0,28	0,14
Lilleham-mer	0,46	0,04	0,14	0,32	0,57	0,02	0,13	0,34	0,00	0,87
Tønsberg	0,44	0,05	0,53	0,03	0,06	0,53	0,22	0,20	0,08	0,46
HIAS	0,00	0,89	0,00	0,88	0,70	0,01	0,20	0,23	0,22	0,21
Nordre Follo	0,00	0,99	0,18	0,26	0,51	0,03	0,42	0,06	0,15	0,31

Regresjonsanlysen viser at det er få sammenhenger mellom de utvalgte variablene og fremmedvann. Særlig når det gjelder nedbør og fremmedvann er dette kanskje overraskende.

Resultatene fra multivariatanalysen gir et mer nyansert bilde av hvilke faktorer som påvirker fremmedvannsandelen enn regresjonsanalysen gjør. Med en multivariatanalyse sammenliknes ulike lokasjoner mot hverandre. Analysen gir derfor ikke entydige svar på hvilke variabler som styrer fremmedvannsmengdene, men den rangerer variablene innad i de ulike områdene. Resultatene fra en multivariatanalyse, som også inkluderer variabelen fellessystem, vises i Figur 12. I figuren har hver variabel blitt rangert etter hvor styrende den er for fremmedvannsmengdene innenfor hvert område.



Figur 12: Resultater fra multivariatanalyse [17]

Resultatene fra multivariatanalysen viser at den av de undersøkte faktorene som bidrar minst til fremmedvannsmengdene er fornyelsestakt av avløpsrør.

4.3. Fremmedvann og drikkevannslekkasjer (artikkel 2 - Påvirkningsfaktorer)

Utlekket drikkevann kan påvirke vannmengdene i avløpsrørene på ulike måter. Små og jevne lekkasjer hvor vannet renner ut fra vannrørene og inn i avløpsrørene vil påvirke den jevne vannstrømmen, mens brudd på vannledninger hvor store vannmengder forsvinner ut i grøften vil kunne påvirke hvordan spissbelastningen ser ut.

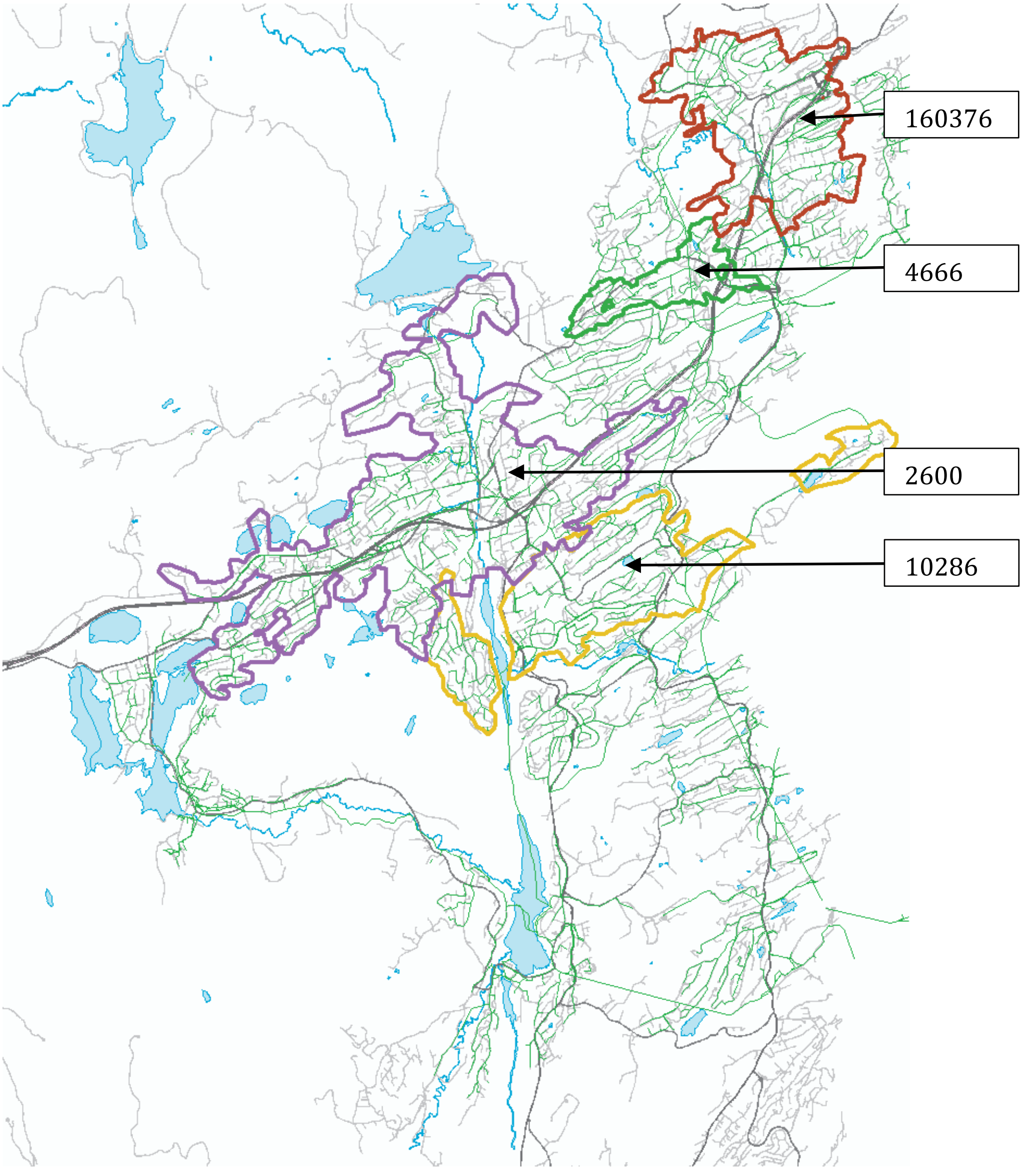
Sommeren 2018 var uvanlig tørr i hele sør- Norge. I Asker falt det i perioden juni/juli/august 46/22/53 mm nedbør mot normalt 72/90/106 mm [17, 41]. Etter en så lang tørkeperiode skulle en anta at fremmedvannsmengdene var minimale, men undersøkelser av avløpsnettet i Asker viser at det også i denne perioden var forholdsvis mye fremmedvann. Tabell 12 angir fire ulike områder hvor det er gjort undersøkelser av fremmedvannsmengder for sommeren 2018. I hvert av områdene stod det ute en vannføringsmåler som kontinuerlig logget vannføringen i avløpsrørene.

Tabell 12: Antall PE tilknyttet ulike undersøkte målesoner

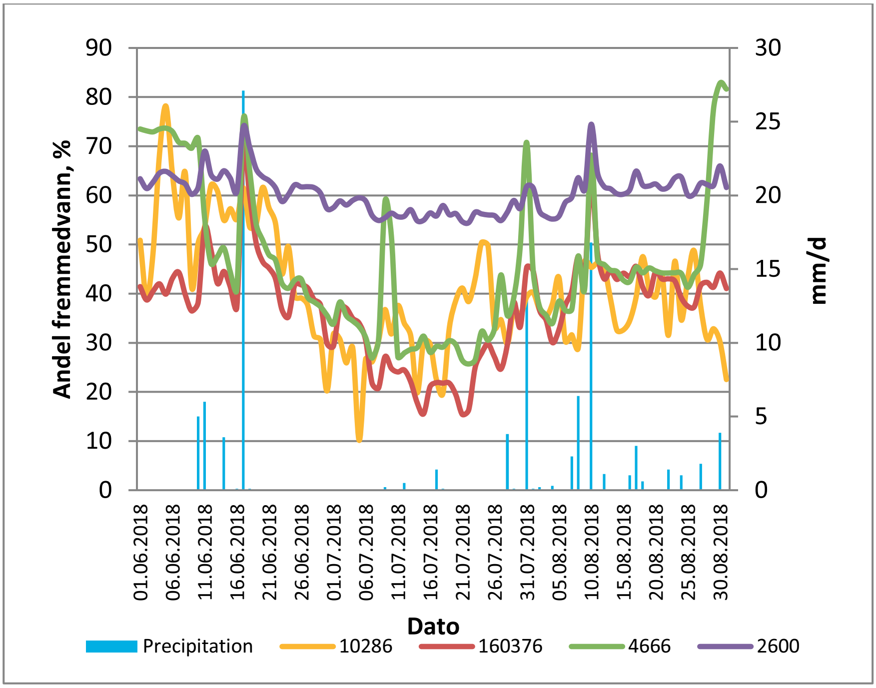
Kum nummer	**Antall tilknyttede PE**
10286	7530
160376	6140
4666	4666
2600	14003

Figur 13 viser målesonene som er brukt i undersøkelser om fremmedvannsmengder sommeren 2018.

Figur 14 viser andeler fremmedvann i Asker for de undersøkte avløpssonene.



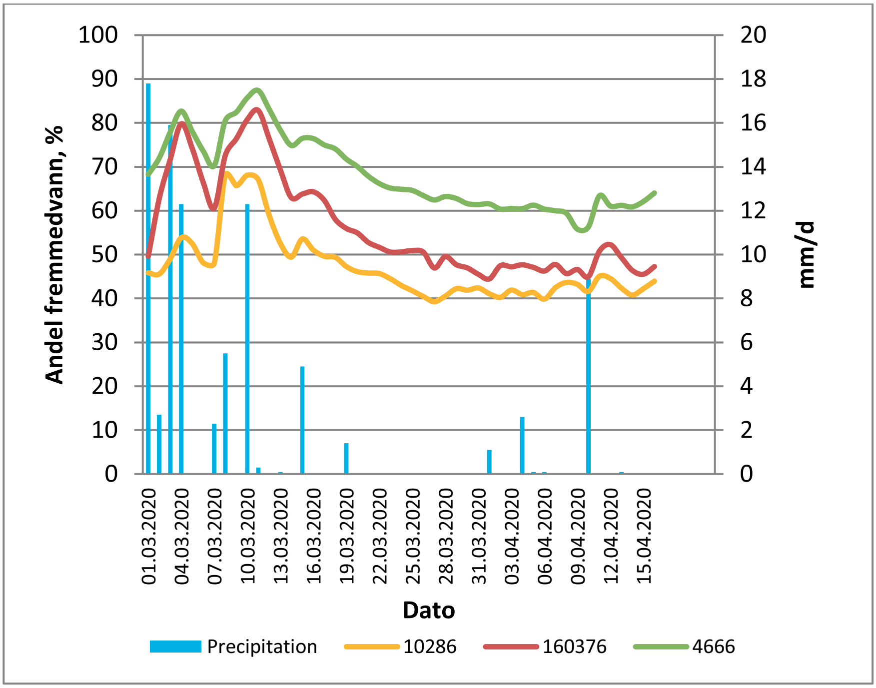
Figur 13: Kart som viser avløps- målesoner hvor fremmedvannsnivået er undersøkt



Figur 14: Fremmedvannmengder i 4 avløpssoner i Asker sommeren 2018 [17]

Det punktet hvor det er beregnet minst fremmedvann har altså til tross for tørke en andel på 10-15%. I dette avrenningsfeltet er det ikke feilkoblet elver/bekker på avløpsnettet, og grunnvannsstanden er antatt å være lav på grunn av minimalt med nedbør. Vi kan derfor anta at de målte mengdene fremmedvann i hovedsak skyldes utlekket drikkevann [17].

Våren 2020 var det igjen en lang periode i Asker uten nedbør. 3 av de samme målepunktene som ble undersøkt for våren 2018 var fortsatt operative i 2020. Det ble derfor gjort en ny undersøkelse av disse tre punktene. Resultatet fra undersøkelsen vises i Figur 15.



Figur 15: Fremmedvannsmengder i Asker våren 2020

Fremmedvannsnivået ligger mye lavere for perioden i 2018 enn for den vurderte perioden i 2020. Det laveste nivået i 2020 er på omtrent 40% fremmedvann av de totale vannmengdene. Dersom det er riktig at innlekket drikkevann utgjør 10-15% av de totale vannmengdene i målepunktene, betyr det at de resterende 25-30% i 2020 skyldes grunnvann. Siden grunnvannsnivået ikke måles i Asker er det vanskelig å si akkurat hvor stor andel dette utgjør, men målingene vist i figurene 15 og 16 antyder at dette kan være tilfelle. Dette vil igjen bety at det må lange tørrværsperioder til før grunnvannet synker under avløpsledningene, og at det de aller fleste dager i året er et stort tilsig av både grunnvann og innlekket drikkevann i avløpsledningene i Asker.

4.4. Kostnadseffektivitetsanalyse (artikkel 3 - Konsekvenser)

Det er gjennom studie 3 gjort en kostnadseffektivitetsvurdering av tre ulike tiltak mot konsekvenser av fremmedvann. De vurderte tiltakene er; A) rehabilitering av alle dårlig rør kombinert med feilsøking etter fremmedvann, B) oppdimensjonering lokalt kombinert med fordrøyning sentralt og C) fordrøyning både lokalt og sentralt. I tillegg er et alternativ 0 vurdert. 0- alternativet innebærer at det gjennomføres et minimum av tiltak; 1% av ledningsnettet rehabiliteres årlig samt en enkel oppgradering av pumpestasjoner. Tiltakene vurderes over en periode på 40 år totalt [1, 42]. Alle tiltakene i alternativ A, B og C gjennomføres over en 5- års periode, mens tiltakene i alternativ 0 gjennomføres over hele perioden på 40 år. Dette inkluderer også feilsøk etter fremmedvann, som er en del av de tiltakene som gjennomføres i alternativ A. Driftsutgifter inkluderes for hele perioden.

Beregnet nåverdi av de vurderte tiltakene vises i Tabell 13.

Tabell 13: Beregnet nåverdi for alle vurderte alternativ [1]

	Alt. 0	Alt. A	Alt. B	Alt. C
	Nåverdi millioner kroner			
Finansielle kostnader				
Generell rørfornying, 1% pr år	-560			
Fornying av dårlige rør		-955	-579	-579
Felt arbeid		-8		
Oppdimensjonering av rør			-115	
Renovering av pumpestasjoner	-125	-125		-125
Oppdim. av pumpe stasjoner			-223	
Drift av pumpestasjoner	-113	-81	-164	-164
Kontinuerlig vedlikehold, VEAS	-253	-253	-253	-253
Driftskostnader, VEAS	-140	-114	-203	-198
Etablering av fordrøyning, VEAS			-285	-231
Etablering av fordrøyning, lokalt				-53
Erstatningsutbetalinger				
Totale kostnader	**-1191**	**-1536**	**-1822**	**-1604**

Alternativ A) rehabilitering av avløpsledninger sammen med økt innsats når det gjelder feilsøk etter fremmedvann er det mest økonomisk lønnsomme tiltaket, bortsett fra alternativ 0. Alternativ A er det eneste tiltaket som vil redusere utlekking av avløpsvann fra utette ledninger. Dette er ikke inkludert i de beregningene som er gjort.

Fremmedvann fører til utslipp av blant annet fosfor. Utslippene vil bli redusert i alle de undersøkte alternativene. Hvor store utslippene vil bli over en 40- års periode vises i Tabell 14.

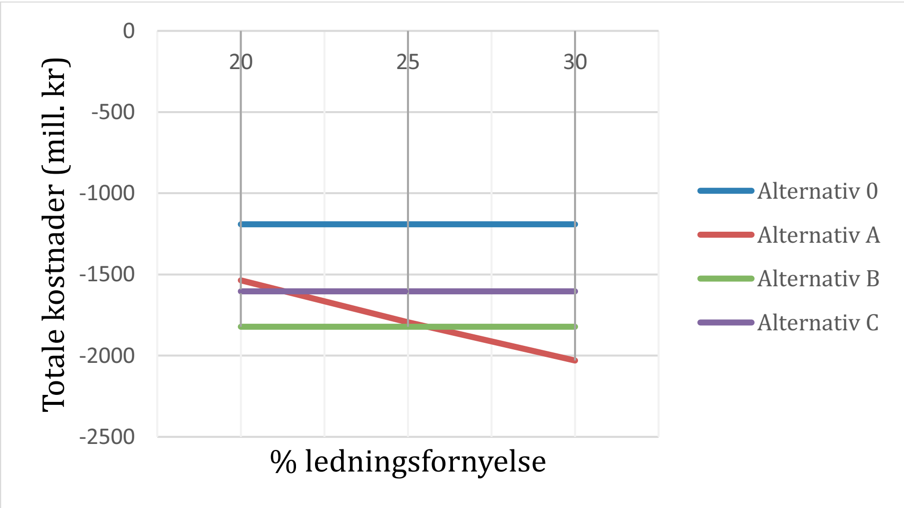
Tabell 14: Utslipp av fosfor som følge av fremmedvann vurdert for alle alternativer [1]

Alternativer	**2017, kg Tot-P**	**2059, kg Tot-P**	**2019-2059, kg Tot-P**
Alternativ 0	1584	1584	64929
Alternativ A	1584	1077	45498
Alternativ B	1584	1152	48384
Alternativ C	1584	1152	48384

I vurderingene av reduserte utslipp ligger blant annet forurensningsregnskap for Asker kommune til grunn. I tillegg er det brukt tall fra VEAS på dagens utslippsmengder. Videre er det antatt at reduksjon i fremmedvannsmengdene vil føre til proporsjonale reduksjoner i utslippsmengdene [1].

I alternativ A koster det 79929 kr å fjerne 1 kg fosfor. I alternativ B, som innebærer oppdimensjonering av lokale pumpestasjoner i kombinasjon med fordrøyning hos VEAS, koster fosforreduksjon 110127 kr/kg og i alternativ C, fordrøyning både lokalt og sentralt, koster det 104863 kr/kg redusert utslipp av fosfor. Alternativ A er altså det mest kostnadseffektive tiltaket [1].

Beregningene som er gjort i alternativ A bygger på antakelsen om at rehabilitering og feilsøking etter feilkoblinger vil resultere i en 50% reduksjon av fremmedvannstilførselen. Det er vanskelig å si noe generelt om hvor stor effekt disse tiltakene vil ha på andel fremmedvann i nettet. Effekt av tiltak vil variere fra sted til sted. Nøye analyser av hvilke kilder til fremmedvann som finnes er nødvendig for å finne de riktige tiltakene. I Asker er alle ledninger lagt før 1975 rørinspisert. Dette gir et godt grunnlag for å kunne si noe om hvilke ledninger som bør rehabiliteres. Erfaringsmessig er det ofte forskjøvne skjøter og sprekker i gamle betongrør, det er derfor sannsynlig at vann kan lekke både inn og ut av slike rør. Denne erfaringen danner grunnlag for den rehabiliteringstakten som er angitt for alternativ A. Dersom det ikke stemmer at vi oppnår 50% reduksjon ved å rehabilitere 20% av rørene, men at vi isteden må rehabilitere en høyere andel, vil de andre tiltakene være mer lønnsomme enn alternativ A.[1]. De totale kostnadene ved ulike renoveringsrater er presentert i Figur 16.



Figur 16: Totale kostnader for ulike alternative renoveringsrater

Dersom vi må renovere ca. 21% av ledningsnettet for å oppnå 50%reduksjon vil alternativ C være mer lønnsomt enn alternativ

A. Dersom vi må renovere ca. 26% av rørene vil både alternativ B og C være mer lønnsomme enn alternativ A.

Kjelleroversvømmelser på grunn av fremmedvann er lite utbredt i Asker. For å unngå kjelleroversvømmelser er det etablert overløp. I områder hvor kjelleroversvømmelser er et gjentakende problem er det viktig å prissette både hva disse oversvømmelsene koster og hva betalingsvilligheten for å unngå slike ulemper er.

4.5. Prissetting av fremmedvann (artikkel 3 - Konsekvenser)

Prisen på fremmedvann vil variere etter hvilken pris en setter på utslipp forårsaket av fremmedvannet. Utslippskostnader sammen med fremmedvannsrelaterte driftskostnader vil utgjøre de totale fremmedvannskostnadene. Et viktig grunnlag for å gjøre et overslag av prisen på fremmedvann er derfor et forurensningsregnskap. Relevante parametere som må inkluderes i beregninger av kostnader av fremmedvann er overløp lokalt, overløp fra renseanlegg og restutslipp fra renseanlegg [1].

Ved å bruke prisen som fremkommer gjennom alternativ A, det mest kostnadseffektive tiltaket, kostet fremmedvannet Asker kommune 138 millioner kroner i 2017. Fjerning av fremmedvann er beregnet til å være økonomisk lønnsomt så lenge prisen på utslipp av fosfor er større enn 17806 kr/kg [1].

4.6. Betalingsvillighet for bedring i vannkvalitet (artikkel 3 - Konsekvenser)

For å kunne gjøre en kost/nytte- analyse er det nødvendig å prissette nytteverdier av de vurderte tiltakene, i tillegg til kostnadene. Relevante aspekt å vurdere i forbindelse med tiltak som ser på bedring av vannkvalitet kan være a) fiskeforhold, b) vannkvalitet og c) badevannskvalitet. En gjennomgang av både norske og europeiske undersøkelser viser hvordan disse vanngodene har blitt verdsatt i ulike undersøkelser av betalingsvillighet. Resultater fra relevante undersøkelser vises i Tabell 15. Tabellen inkluderer også en undersøkelse angående betalingsvillighet for å unngå kjelleroversvømmelser.

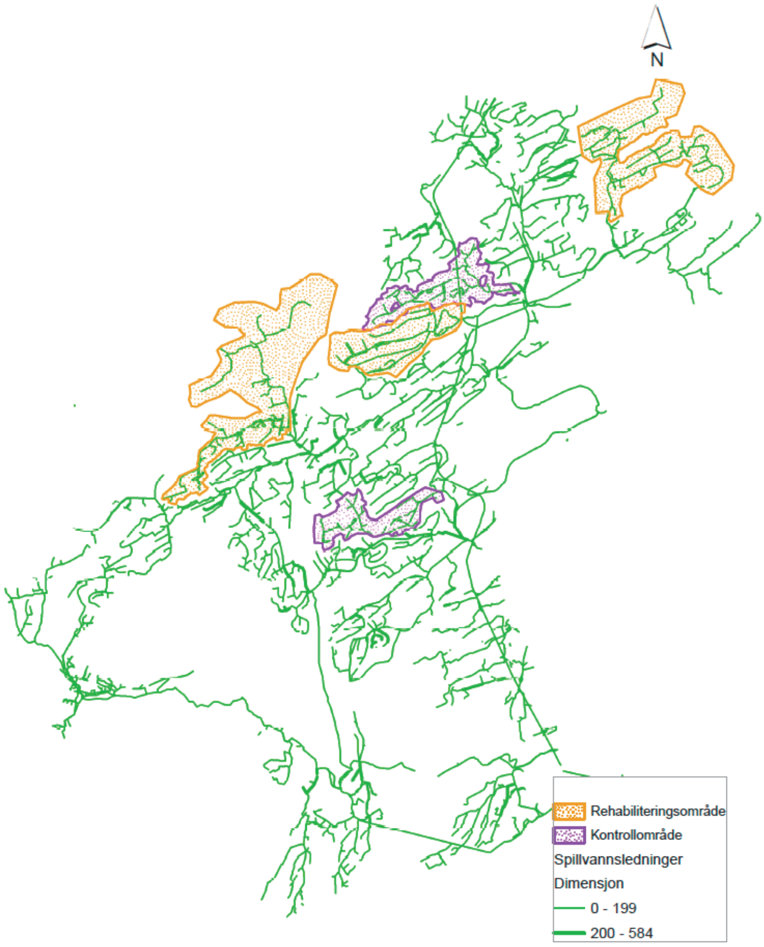
Tabell 15: Oppsummering av tall brukt i beregninger av betalingsvillighet for å oppnå bedring i vannkvalitet (2018- verdier) [1, 43-48]

Område	Land	Nedre verdi (kroner)	Øvre verdi (kroner)
Gode fiskeforhold (engangs sum)	Norge	734	1893
Bedre vannkvalitet (person/år)	Norge	554	2709
Bedret badevannskvalitet (person/år)	Irland/ Danmark	86	1176
Bedret vannkvalitet (person/år)	Sverige	260	303
Unngåtte kjelleroversvømmelser (pr hus)	Norge	400	800

Pr 2018 bodde det ca. 61400 personer i Asker [49]. Ved å bruke en middelverdi for betalingsvillighet for bedring i vannkvalitet basert på norske verdier, nemlig 1632 kr/person og år, utgjør dette ca. 1999 millioner kroner over 40 år. Dette er en høyere sum enn kostnadene for alle de vurderte tiltaksalternativene. Det er derfor rimelig å anta at det er samfunnsøkonomisk lønnsomt å øke innsatsen for å hindre et dårlig fungerende avløpsnett i å forringe viktige økosystemtjenester.

4.7. Effekt av tiltak mot fremmedvann (artikkel 4 - Tiltak)

Hensikten med studie nummer 4 er todelt. Studien vurderer hvorvidt det er hensiktsmessig å innføre kontrollområder for å dokumentere effekt av tiltak mot fremmedvann, og den undersøker hvilken effekt tradisjonelle rehabiliteringstiltak har på fremmedvannsmengdene i avløpsnettet. Det er utført undersøkelser i tre ulike rehabiliteringsområder; Dæli og Vakås med kontrollområde J.R.Wilhelmsens vei (JRWs vei), og Vestre vei med kontrollområde Holmen. Alle områdene vises i Figur 17.



Figur 17: Kart over rehabiliteringsområder og kontrollområder

Sammenlikning av resultater for ulike tørrværsperioder før og etter tiltak for Vakås og Dæli vises i Tabell 16. Tabell 17 viser sammenlikning av ulike nedbørsperioder for Vakås og Dæli før og etter tiltak.

Tabell 16: Sammenligning av resultater for tørrværsperioder for Vakås og Dæli mot kontrollområdet JRWs vei [35]

tørrvær			
	før rehab. (12.02.2016-26.02.2016)	etter rehab. (04.05.2018-13.05.2018)	endring
JRWs vei (kontrollomr.)	74%	78%	+4 ↑
Vakås (rehab. område)	86%	81%	- 5 ↓
Dæli (rehab. område)	66%	70%	+4 ↑
	før rehab. (12.02.2016-26.02.2016)	etter rehab. (16.05.2018-27.05.2018)	endring
JRWs vei (kontrollomr.)	74%	74%	0 →
Vakås (rehab. område)	86%	64%	- 22 ↓
Dæli (rehab. område)	66%	61%	- 5 ↓
	før rehab. (31.08.2016-10.09.2016)	etter rehab (04.05.2018-13.05.2018)	endring
JRWs vei (kontrollomr.)	85%	78%	- 7 ↓
Vakås (rehab. område)	85%	81%	- 4 ↓
Dæli (rehab. område)	63%	70%	+7 ↑
	før rehab. (31.08.2016-10.09.2016)	etter rehab. (16.05-2018-27.05.2018)	endring
JRWs vei (kontrollomr.)	85%	78%	- 7 ↓
Vakås (rehab. area)	85%	64%	- 21 ↓
Dæli (rehab. area)	63%	61%	- 2 ↓

Tabell 17: Sammenlikning av resultater for ulike nedbørsperioder for områdene Vakås og Dæli mot JRWs vei [35]

nedbør			
	før rehab. (18.05.2016-01.06.2016)	etter rehab. (04.05.2018-13.05.2018)	endring
JRWs vei (kontrollomr.)	87%	82%	- 5 ⬇
Vakås (rehab. område)	87%	79%	- 8 ⬇
Dæli (rehab. område)	70%	58%	- 12 ⬇
	før rehab. (18.08.2016-02.09.2016)	etter rehab. (07.02.2018-25.02.2018)	endring
JRWs vei (kontrollomr.)	86%	81%	- 5 ⬇
Vakås (rehab. område)	88%	75%	- 13 ⬇
Dæli (rehab. område)	68%	54%	- 14 ⬇

For områdene Vakås og Dæli, begge uten overløp, viser målinger av vannføring før og etter tiltak at fremmedvannsmengdene gikk ned etter rehabilitering. For Vakås var det en positiv endring, både i tørrvær og under nedbør, mens det for Dæli ikke kan sees en tydelig nedgang i fremmedvannsmengdene i tørrværsperioder.

Resultatene fra undersøkelsene summeres opp i Tabell 18.

Tabell 18: Oppsummering av fremmedvannsreduksjon for områdene Vakås and Dæli [35]

	Fremmedvannsreduksjon (%poeng)	
Område	**Tørrvær**	**Nedbør**
Vakås	9 - 22	3 - 8
Dæli	0	7 - 9

Sammenlikning av resultater for ulike tørrværsperioder for Vestre vei vises i Tabell 19. Tabell 20 viser sammenlikning av resultater for ulike nedbørsperioder for Vestre vei før og etter tiltak.

Tabell 19: Sammenlikning av tørrværsperioder for området Vestre vei mot Holmen [35]

tørrvær			
	før rehab. (08.12.2017-25.12.2017)	etter rehab. (06.08.2019-09.08.2019)	endring
Holmen (kontrollomr.)	45%	48%	+3
Vestre vei (rehab. område)	46%	60%	+14
	før rehab. (29.05.2018-09.06.2018)	etter rehab. (06.08.2019-09.08.2019)	endring
Holmen (kontrollomr.)	69%	48%	- 21
Vestre vei (rehab. område)	56%	60%	+4
	før rehab. (19.06.2018-08.07.2018)	etter rehab (15.09.2019-19.09.2019)	endring
Holmen (kontrollomr.)	31%	51%	+20
Vestre vei (rehab. område)	52%	56%	+4

Tabell 20: Sammenlikning av resultater for ulike nedbørsperioder for Vestre vei mot Holmen [35]

nedbør			
	før rehab. (05.11.2017-10.11.2017)	etter rehab. (28.08.2019-29.08.2019)	endring
Holmen (kontrollomr.)	62%	67%	+5 ↑
Vestre vei (rehab. område)	37%	64%	+27 ↑
	før rehab. (28.07.2018-12.08.2018)	etter rehab. (10.08.2019-12.08.2019)	endring
Holmen (kontrollomr.)	37%	75%	+38 ↑
Vestre vei (rehab. område)	62%	57%	- 5 ↓
	før rehab. (05.09.2018-11.09.2018)	etter rehab (27.09.2019-04.10.2019)	endring
Holmen (kontrollomr.)	68%	77%	+9 ↑
Vestre vei (rehab. område)	65%	63%	- 2 ↓

Resultatene fra undersøkelsene av Vestre vei er summert opp i Tabell 21.

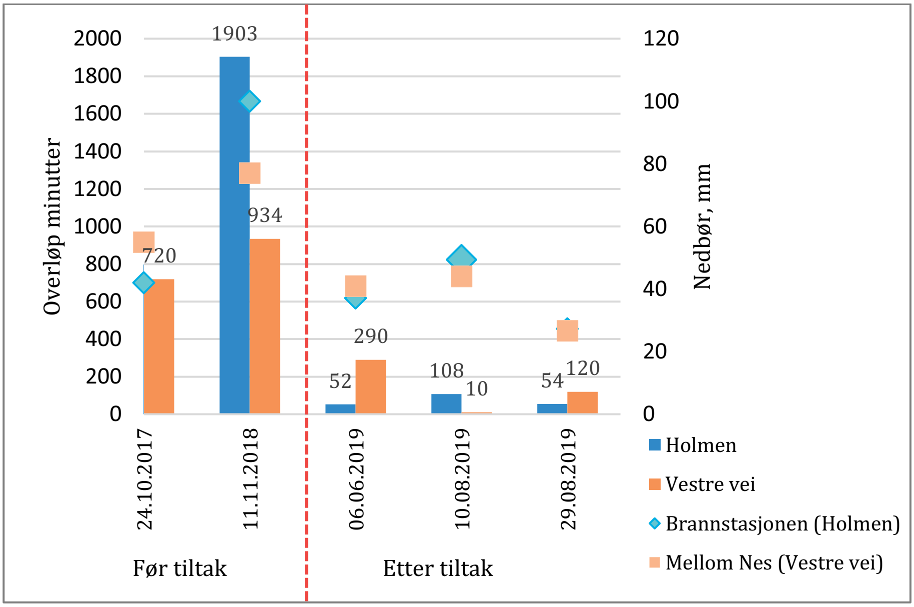
Tabell 21: Oppsummering av fremmedvannsreduksjon for Vestre vei [35]

	Fremmedvannsreduksjon (% poeng)	
Område	**Tørrvær**	**Nedbør**
Vestre vei	0	11 - 43

For området Vestre vei viser målinger at det i tørrvær ikke er noe positiv endring i fremmedvannsnivået, men det for nedbørsperioder kan sees en positiv utvikling.

Det er altså sannsynlig at de gjennomførte tiltakene har hatt en viss effekt på fremmedvannsnivåene i alle de tre undersøkte områdene, men reduksjonen er minimal særlig for Dæli- området.

For området med overløp, Vestre vei, er det også gjort en vurdering av om tiltakene har påvirket overløpsdriften i positiv retning. Overløpsdrift før og etter tiltak vises i Figur 18. Både for området Vestre vei og området Holmen (kontrollområde) er det hentet ut nedbørsdata fra to ulike nedbørstasjoner; Brannstasjonen og Mellom Nes. Brannstasjonen ligger geografisk nærmest Holmen, mens Mellom Nes er plassert nærmest Vestre vei.



Figur 18: Registrert overløpsdrift før og etter tiltak i Vestre vei [35]

Figuren viser at når det før tiltak er registrert tilnærmet like mye nedbør over to avløpssonene, så vil de gå tilnærmet like mye i overløp (24.10.2017). Ved hendelsen den 11.11.2018 regner det mer over Holmen enn over Vestre vei, da går det også tilsvarende mer i overløp fra Holmen- området enn fra Vestre vei [35].

Etter tiltak ser vi en nedgang i overløpsdrift. Nedgangen finner vi både i rehabiliteringsområdet og i kontrollområdet. Hendelsen den 10.08.2019 er tilsvarende stor som hendelsen 24.10.2017 når det gjelder nedbør. Dersom vi ikke hadde benyttet et kontrollområde hadde det vært mulige å feilaktig konkludere med at overløpsdriften er redusert basert på målinger fra disse to hendelsene. Men vi ser at overløpsdriften er redusert tilsvarende for kontrollområdet som for rehabiliteringsområdet og kan derfor ikke konkludere med at de gjennomførte tiltakene har hatt effekt på overløpsdrift.

Ved å rehabilitere en liten del av avløpsnettet oppnår vi en liten reduksjon i fremmedvannsmengdene. Ved å måle på mindre områder vil en sannsynligvis øke andelen fremmedvannsreduksjon, fordi andelen rehabiliterte spillvannsledninger da blir høyere i dette mindre området.
Hvis man skal få en betydelig reduksjon av fremmedvannsmengdene som følge av rehabilitering av spillvannsledninger, må andelen rehabiliterte ledninger bli betydelig høyere enn det som er vist i denne undersøkelsen.

5. Usikkerheter

Det er gjort en vurdering av usikkerheter knyttet til data for alle de gjennomførte undersøkelsene. Grønn farge indikerer at påliteligheten til grunnlagsdataene er høy, men rød farge indikerer at dataene som er brukt har høy usikkerhet. Hvordan påliteligheten til grunnlagsdataene er vurdert vises i Tabell 22.

Tabell 22: Vurdering av pålitelighet for grunnlagsdata [1, 14, 17, 35]

		Pålitelighet		
Artikkel nr.	**Grunnlagsdata**	**Høy**	**Medium**	**Lav**
1	Antall PE			
1	Drikkevannsforbruk			
1	Fosforproduksjon			
1	Konsentrasjon av ToT-P inn til renseanlegg			
1, 3	Vannføring i avløpsrør			
1, 2, 3, 4	Nedbørsmengder			
2	Drikkevannslekkasjer			
2	Leverte andeler drikkevann			
2	Alder på ledningsnett			
2	Historisk fornyelsestakt på ledningsnett			
2	Andel fellessystem			
3	Rørkvalitet			
3, 4	Overløpsdrift i Asker			
3	Overløpsdrift fra VEAS			
1,2, 3, 4	Andeler fremmedvann			
3	Reduserte andeler fremmedvann			
3	Reduserte driftskostnader, Asker			
3	Reduserte driftskostnader, VEAS			
3	Kostnader for oppdimensjonering av pumpestasjoner			
3	Kostnader for etablering av fordrøyningsbasseng			
3	Kostnader knyttet til rørfornying			

Bare tallene på andeler reduserte fremmedvannsmengder benyttet i artikkel om konsekvenser av fremmedvann, er vurdert til å være lite pålitelige.

6. Oppsummerende konklusjoner

Mange norske kommuner overvåker avløpsnettet og har derfor tilgang til data for relevante analyser av blant annet fremmedvann. Målinger av vannføring i avløpsnettet kan utgjøre basisen i systematisk arbeid med fremmedvann.

Hvilken metode som brukes til å beregne andel fremmedvann har betydning. Det er derfor viktig å være konsekvent i valg av metode for å kunne si noe om utviklingen av fremmedvann over tid. Hvor nøyaktige tall som finnes på overløpsdrift, drikkevannsforbruk og fosforproduksjon vil også være avgjørende for hvor godt egnet både vannbalansemetoden og fortynningsmetoden (fosformetoden) er til å anslå andel fremmedvann i avløpsnettet.

Av de nordiske landene er andel fremmedvann høyest i Norge. Dette skyldes en rekke variable, men nedbørsmønstre, sesongvariasjoner og svingninger i temperatur, andel fellessystem og leggedyp på ledningsnettet bidrar sannsynligvis til de høye andelene i Norge spesielt. Utviklingen er for mange av de undersøkte norske kommunene god, hvilket innebærer at andel fremmedvann har gått ned de siste årene, til tross for økte nedbørsmengder. Også i Sverige kan vi se en positiv utvikling, mens andelene fremmedvann i Danmark og Finland holder seg på et stabilt og forholdsvis lavt nivå.

Med en multivariat analyseteknikk kan flere variabler korreleres samtidig, i motsetning til en standard regresjonsanalyse hvor en og en variabel undersøkes om gangen. En multivariatanalyse kan derfor avdekke mønstre i datasett som det ellers kan være vanskelig å se. Multivariatanalysen som er gjort i foreliggende arbeid viser at alle de undersøkte variablene bidrar til fremmedvann, bortsett fra rehabiliteringstakt på avløpsnettet. Nedbør er av betydning for fremmedvannsmengdene, men også utlekket drikkevann, andeler fellessystem og alder på avløpsledningsnettet spiller en rolle. Det varierer fra sted til sted hvilke av variablene som har størst påvirkningskraft.

For undersøkte områder i Asker er det sannsynlig at lekkasjer fra drikkevann påvirker det jevne tilsiget av fremmedvann. Målinger fra tørre perioder antyder også at grunnvannet påvirker i stor grad. Målinger fra sommeren 2018 viser at innlekking fra drikkevannslekkasjer antakelig utgjør så mye som 10-15% av de totale avløpsmengdene, mens målinger fra våren 2020 antyder at grunnvannsbidraget er på 25-30 %. Grunnvann måles i liten grad i Norge. Hvordan samspillet mellom avløpssystemet og grunnvannet er bør undersøkes i mye større grad enn det som gjøres i Norge i dag.

Bærekraftsbegrepet er tradisjonelt knyttet til et økonomisk, sosialt og miljømessig perspektiv. Fremmedvann kan føre til både økte utgifter, forsøpling, kjelleroversvømmelser og forringelse av resipientkvalitet. Et avløpssystem hvor fremmedvann fører til uønskede konsekvenser er ikke bærekraftig.

Fremmedvannet påvirker drift av pumpestasjoner. I beregninger gjort for Asker gjennom foreliggende arbeid, hvor vi reduserer fremmedvannet med 50% i løpet av 5 år, vil kostnader knyttet til drift av pumpestasjonene reduseres med totalt 1,5 millioner i løpet av 5 år. Fremmedvannsrelaterte utslipp vil reduseres med 316,7 kg i løpet av de samme 5 årene. Ved å sette en pris på fosforutslipp på ca. 17000 kr/kg utgjør disse 316 kiloene om lag 5,38 millioner kroner. Det er derfor veldig viktig å inkludere kostnader relatert til utslipp i regnestykker om fremmedvannskostnader for å kunne si om tiltak mot fremmedvann lønner seg eller ikke.

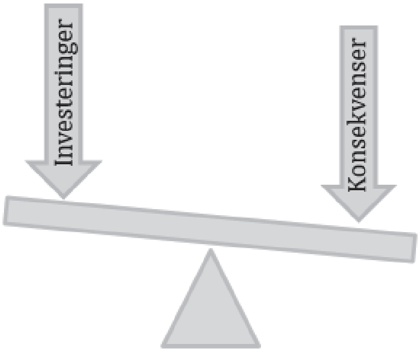
Planlegging og gjennomføring av tiltak kan gjøres på mange ulike måter. Tiltakene kan pågå over lang tid eller det kan settes inn store ressurser på å gjennomføre mange tiltak på kort tid. Hvilken strategi som velges bør styres blant annet etter hvilken tilstand resipienten har. I en sårbar resipient som lider under for store utslipp bør utslippene prissettes høyere enn i en god resipient som tåler utslipp bedre.

Hvilket investeringsnivå som er riktig vil også kunne variere år for år. Siden fremmedvannsnivået i stor grad er styrt av nedbørsmengder kan en tenke seg at det enkelte år er større behov for tiltak enn andre. Slike «fleksible» tiltak er vanskelig å gjennomføre i praksis, men fordrøyningsbasseng kan være et eksempel på et slik «fleksibelt tiltak». Bassengene kan tas i bruk når det er nødvendig.

Betalingsvillighet kan brukes som et mål på hva et miljøgode er verdt. Dersom befolkningen er villig til å betale mye for å få for eksempel reint badevann betyr det at utslipp av næringsstoffer/bakterier bør prises høyt. Det vil i et sånt eksempel være grunnlag for å sette i verk mange tiltak for å redusere utslippene. Betalingsvilligheten kan for eksempel brukes til å prissette en viss økosystemtjeneste. En slik tjeneste vil som oftest ikke kunne brukes fullt ut med mindre alle tiltak er gjennomført og forventet effekt er oppnådd. Likevel kan undersøkelser av betalingsvillighet gi oss en pekepinn på hvorvidt det er grunnlag for å sette i gang med omfattende tiltak eller ikke. I Figur 19 er det illustrert hva som bør inkluderes i vurderinger av tiltak mot fremmedvann. Å innfri myndighetskrav, vurdere resipientkvalitet og å bruke undersøkelser av betalingsvillighet som rettesnor er de viktigste styringspunktene en har når det gjelder hvorvidt det bør investeres i tiltak mot fremmedvann eller ikke.

Figur 19: Forhold som styrer innsatsen mot fremmedvann

Investeringsnivået bør stå i forhold til hvilke konsekvenser fremmedvannet gir, som illustrert i Figur 20.



Figur 20: Investeringsnivå balansert mot konsekvenser

Et bærekraftig fremmedvannsnivå har vi dersom alle myndighetskrav er oppnådd og de investeringene som må til for å kvitte seg med fremmedvann er lavere enn den nytten vi oppnår dersom fremmedvannsnivået reduseres. For at dette regnestykket skal bli riktig er det viktig å prissette alle konsekvenser av fremmedvann, også de miljømessige2.

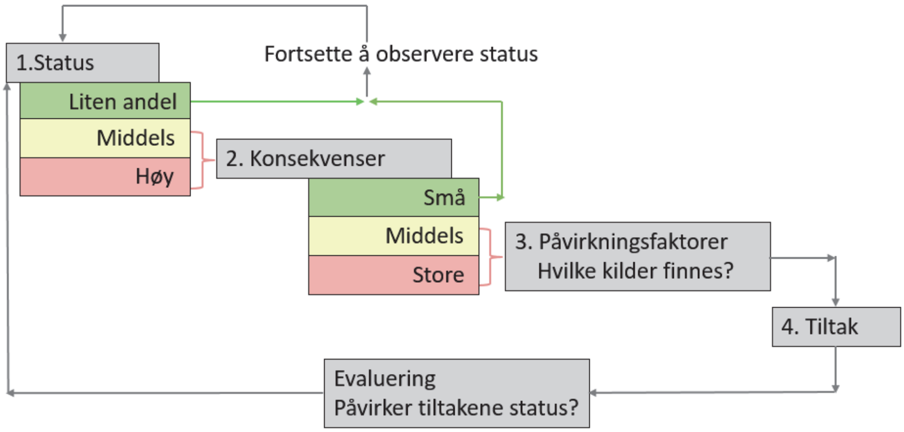
Det er vanskelig å skulle dokumentere effekt av tiltak mot fremmedvann. Utfordringen ligger i at store andeler av fremmedvannet som oftest er styrt av nedbør. Det er vanskelig å finne to helt like og sammenliknbare nedbørsituasjoner. Ved å sammenlikne målt vannføring ikke bare i tiltaksområder, men også i områder hvor det ikke er gjennomført tiltak, har vi et bedre grunnlag for å dokumentere hvorvidt de gjennomførte tiltakene har hatt effekt eller ikke.

En mye brukt metode for å redusere fremmedvann er rehabilitering av avløpsledninger. Ved undersøkelser av 3 rehabiliteringsområder i Asker er det dokumentert at rehabilitering reduserer andel fremmedvann i avløpsnettet til en viss grad. Det er vanskelig å finne tydelig effekt av tiltakene under tørrværsperioder, men under nedbør ser vi en reduksjon på noen prosentpoeng. Den største dokumenterte reduksjonen ligger et sted mellom 11 og 43 prosentpoeng. Det er ikke mulig å konkludere med at tiltakene har gitt effekt på overløpsdrift. Innenfor målesonene er det bare rehabilitert om lag 10% av det kommunale ledningsnettet. Resultatene hadde sannsynligvis blitt bedre dersom andelen fornyede ledninger hadde vært større.

Tallene på andeler reduserte fremmedvannsmengder benyttet i artikkel 3 er vurdert til å være lite pålitelige. Denne antagelsen er bekreftet gjennom artikkel 4, hvor andelene som er fjernet med rehabiliteringstiltak er lave. Tiltaket som inkluderer oppdimensjonering lokalt og fordrøyning sentralt (alternativ B), i artikkel 3, vil derfor mest sannsynlig være mer lønnsomt enn tiltaket som inkluderer rehabilitering (alternativ A). Denne konklusjonen er også understøttet gjennom artikkel 2, hvor fornyelsestakt på avløpsledninger er den av de undersøkte variablene som sannsynligvis bidrar minst til fremmedvannsmengdene. Det er viktig å påpeke at tiltak på avløpsledningene ofte er motivert av mange faktorer, og at fremmedvann bare er en slik faktor.

Dersom fremmedvannsmengdene skal reduseres betydelig må sannsynligvis veldig store andeler av avløpsnettet rehabiliteres. Andre tiltak, som rehabilitering av drikkevannsledninger eller feilsøk etter feilkoblinger vil muligens gi mer effektiv bruk av vann- og avløpsmidler.

Metodikken som er utviklet gjennom disse forskningsarbeidene, og som er illustrert innledningsvis i figur 6, kan nyanseres som vist i Figur 21.



Figur 21: Arbeidsmetodikk som kan brukes i systematisk arbeid med fremmedvann

7. Videre arbeid

Arbeidet med denne doktorgraden gir en pekepinn på hvilke forhold rundt fremmedvann som bør undersøkes videre.

Først og fremst bør det undersøkes hvilken effekt andre tiltak enn rehabilitering av avløpsrør kan gi på andeler redusert fremmedvann. For eksempel bør det undersøkes hvordan renovering av drikkevannsledninger påvirker fremmedvannsandelene. Med et ellers velfungerende avløpsnett kan muligens et slikt tiltak være mer kostnadseffektivt enn å rehabilitere avløpsledningene dersom målet med tiltaket bare er å kvitte seg med fremmedvann. Videre bør det undersøkes om tiltak bare rettet mot kummer kan være et alternativ til ledningsrehabilitering. Det bør undersøkes om utskiftning av kumlokk eller kumtopper, eller renovering av hele kummer, gir tilsvarende effekt på fremmedvannmengder som tiltak på ledningsanlegg.

Det finnes mange grunner til at rør velges ut til rehabilitering. Fjerning av fremmedvann er bare en slik grunn. Forlengelse av levetid og tetting av rør for å forhindre at avløpsvann renner ut av rørene er to andre grunner for å rehabilitere ledninger. Undersøkelser som ser på effekt av rehabiliteringer med tanke på utlekket avløpsvann bør undersøkes.

De undersøkelsene som er gjort viser at det er sannsynlig at grunnvannspåvirkningen er stor i Asker. Grunnvannsnivå bør i større grad måles enn det som er vanlig i Norge i dag.

Multivariatanalyser kan være et godt hjelpemiddel for å rangere ulike påvirkningsfaktorer mot hverandre. Dersom sånne analyser gjennomføres på mindre områder, hvor en har kontroll på de fleste faktorene og dermed reduserer usikkerheten, vil de kunne være et godt supplement til andre metoder som brukes i dag for å finne kilder til fremmedvann. Den demonstrerte metoden kan for eksempel utvides til også å inkludere grunnvannsnivå, andel tette flater og antall bekkekryssinger.

Lokale overvannstiltak bidrar til at større mengder overvann infiltreres i grunnen. Det bør gjøres undersøkelser av i hvilken grad dette påvirker fremmedvannsmengdene.

Undersøkelser av betalingsvillighet kan blant annet brukes til å prissette vannrelaterte tjenester. Ved å gjennomføre betalingsvillighetsundersøkelser spesifikke mot vann- og avløpstjenester vil dette kunne gi oss en pekepinn på om det er grunnlag for å øremerke mer midler til økt innsats mot fremmedvann.

Sårbarhetsvurderinger av resipienter bør inkluderes når tiltak mot fremmedvann skal vurderes. Utslipp i svært sårbare resipienter bør prises høyere enn utslipp i mer robuste resipienter. Uansett resipienttilstand bør det settes en minimumspris på utslipp av stoffer som kan medføre forringelse av økosystemtjenester.

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2019	Identifying factors influencing infiltration and inflow (I/I-water) in wastewater systems using multivariate data analysis	K.J.Sola K.Kvaal O.G.Lindholm J.T.Bjerkoholt H.Ranaweera	VANN
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Infiltration and Inflow (I/I) to Wastewater Systems in Norway, Sweden, Denmark, and Finland

Kristin Jenssen Sola [1,2,*], Jarle Tommy Bjerkholt [1,3], Oddvar Georg Lindholm [1] and Harsha Ratnaweera [1]

1 Faculty of Mathematical Sciences and Technology, Norwegian University of Life sciences, 1430 Ås, Norway; jarle.t.bjerkholt@usn.no (J.T.B.); oddvar.lindholm@nmbu.no (O.G.L.); harsha.ratnaweera@nmbu.no (H.R.)
2 The Municipality of Asker, 1372 Asker, Norway
3 Faculty of Technology, Natural Sciences and Maritime Sciences, University of South-Eastern Norway, 3603 Kongsberg, Norway
* Correspondence: kristin.jenssen.sola@asker.kommune.no; Tel.: +47-41-63-21-84

Received: 29 October 2018; Accepted: 17 November 2018; Published: 21 November 2018

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Abstract: Infiltration and inflow of non-sewer water to the wastewater network (I/I-water) may have a number of both financial and environmental consequences. In Norway, there are two commonly used methods for calculating the volume of I/I-water, The Dilution method (DM) and the Water Balance Method (WBM). When comparing the methods, the WBM gives a lower value of I/I-water than the DM. Analysis shows that the volume of I/I-water for some large Norwegian wastewater plants is decreasing. From 2009 to 2016, the average value has decreased from 70% to 66% of the total annual flow. For investigated Danish districts the average amount of I/I-water is stable, on about 30%. Calculations performed by the Finnish Water Utilities Association shows a stable percentage of I/I-water on about 40% in Finland from 2010 to 2016. Calculations on Swedish wastewater plants show a reduction in I/I-water from 58% to 46% from 2010 to 2016. For the districts Asker, Bærum, and Drammen in Norway, the amount of I/I-water is increasing with increasing percentage of combined sewer systems. This is also the case for investigated plants in Norway, Sweden, and Finland. The exception is Denmark, with a high percentage of combined systems, but a low percentage of I/I-water. Investigations done for Asker, Bærum, Drammen, and the two Danish districts Randers and Esbjerg vest, show a correlation between rainfall and I/I-water only for Asker and Esbjerg vest.

Keywords: I-I-water; sewer; wastewater; precipitation

1. Introduction

Infiltration and inflow of non-sewer water to the wastewater network (I/I-water) is, in the following study, defined as all water entering the sewerage network except sewerage. The level of I/I-water is an indication on how well the wastewater system works in comparison to the intentions. Sources of I/I-water are rainfall, groundwater, and leakages from the water supply system. I/I-water finds its way into the wastewater network through damaged pipes, damaged manholes and fault connections, but can also enter intentionally, which is the case for rainwater in a combined sewer system. In a study by Helen Karstensen [1], the economic consequences of I/I-water for the Bekkelaget drainage area in Oslo were analyzed. Based on the lowest estimates, the study concluded that I/I-water has an annual cost of about NOK 35 million for the city of Oslo. The highest estimates in her calculations gave an annual cost of I/I-water for Oslo of NOK 313.2 million [1]. (Oslo have 674,000 inhabitants in 2018). I/I-water increases the operating costs for a wastewater system, for example pumping costs and treatment costs. In addition, I/I-water contributes to pollution transport through weirs and increased emissions from wastewater treatment plants [2,3].

In Table 1 the consequences of I/I-water are listed.

Table 1. Potential unwanted consequences of infiltration and inflow of non-sewer water to the wastewater network (I/I-water) in wastewater systems.

Component	Consequences
Pumping station	Increased expenses related to maintenance Increased expenses related to energy use
Sewer network included weirs	Payments related to basement floodings Wastewater transported to the recipients
Wastewater treatment plants included weirs	Increased expenses related to maintenance Increased expenses related to energy use Wastewater transported to the recipients

The proportion of I/I-water in wastewater pipes normally in Norway is calculated by using two different methods:

The Dilution method (DM) uses input data of total phosphorus concentration to wastewater treatment plants to calculate the amount of I/I-water. In order to use this method, one must make assumptions on total phosphorus production per person per day (TOT-P/person day) and on the total water consumption per person per day (liter/person day) [4].

The Water Balance Method (WBM) uses measured amounts of water led to a given measuring point to calculate the quantity of I/I-water. In order to use this method, one must make assumptions of the total number of persons and industry connected to the pipes upstream the measuring point and on the water consumption per person and day (liter/person day) [5].

A study by Lindholm and Bjerkholt [4], using data for 2008, concluded that the amount of I/I-water to some large wastewater treatment plants in Norway on average was between 60% and 70% of the total inflow during the whole year. In this study, the DM was used to calculate the percentage of I/I-water. Figures on inlet concentrations of total phosphorus where supplied from the Norwegian Environmental Agency. The water consumption was on an average set to be 160 L/person per day and the phosphorus production was assumed to be 1.8 g/person per day [4].

The study from 2011 was followed up by an investigation of the situation on I/I-water in the Nordic countries [5]. In this study, I/I-water in Norway, Denmark, Finland, and Sweden was investigated. Based on the 2009 data, the DM was used to calculate the amount of I/I-water for some large wastewater treatment plants in Norway (68%), Finland (29%), and Sweden (58%) [5]. Due to lack of information on phosphorus production per person and day for Denmark, it was not possible to use the DM to calculate the amount of I/I-water. The WBM was used instead. For Denmark, the amount of I/I-water was 33%.

To know exactly how high the consumption of water is, it is a necessity to have full coverage of water meters. If a district is not fully covered or have no meters at all, the consumption of water will be based wholly or partly on estimates. Vråle [3] concluded that estimated quantities of water consumed in many Norwegian municipalities often were set to be too high. This is supported by studies conducted in the Drammen region, where residential areas with 100% water meter coverage showed consumption between 109 and 135 L/pe [6]. In order to make calculations of the fraction of I/I-water, it is necessary to have a proper knowledge of water consumption [3]. Norsk Vann (The Norwegian Water) recommends that the specific water consumption, when dimensioning plants, should be about 140 L/s [7].

In 2014, a project was conducted on behalf of the municipality of Oslo (the department of water and wastewater works, VAV). The purpose of the project was to look into how the consumption of water could be reduced most efficiently. As a consequence of this project, information on water consumption was collected from Norway, Finland, Denmark, and Sweden. For Norway, the consumption varied between 240 L/p day (for those with less than 80% water meter coverage) and 137 L/p day (for Drammen municipality with approximately 82% water meter coverage) [8]. For Sweden, it was reported that household consumption for the Stockholm area was about 200 L/p day, and for the Gothenburg area 156 L/p day. Household consumption in Denmark was reported to be 107 L/p in 2013, as an average for the whole country. For Finland, it was stated that the net consumption was assumed to be at about 140 L/p [8].

In Norway, it is common to use 1.8 g TOT-P per person per day when calculating Phosphorus production and dimensioning wastewater treatment plants (WWTP) [4,9]. The WWTP receives wastewater with various concentrations of phosphorus depending on connected industry. Vråle [10] points out that there are big variations in use/production of phosphorus and that it are difficult to make a general recommendation on what values to use in calculations. It is also possible that the infiltration of water to the wastewater system may be of importance, and may lead to an increased content of phosphorus [11].

Due to climate change, an increase in precipitation for the Nordic countries is expected. The annual average precipitation for mainland Norway has increased by almost 20% since 1900 [12]. In Denmark, the annual average precipitation has increased about 15% from 1874 to 2013 [13]. The correlation between increased precipitation and increased amounts of water in drainage pipes can be investigated, for instance, by using hydraulic and hydrologic models. This was done in a study from Oslo, where various factors that could affect the I/I-% were examined [14]. The factors considered were the fraction of combined to separate systems, the average age of the sewer pipes, the area of sealed surfaces compared to permeable surface, precipitation, number of crossings between sewer pipes and piped streams/open water courses. As a tool, a simplified and calibrated hydrological model, similar to Mouse RDII developed by DHI, was used [14]. The study concluded that I/I-water is a highly variable component which is difficult to predict from characteristics within different drainage fields [14].

I/I-water has been paid some attention in recent studies, most of which have emphasized identifying sources of I/I-water, quantifying shares in the I/I-water and to give an understanding on what the situation regarding I/I-water is of today [15–18]. The main goal of the study presented in this article was investigating the status of I/I-water in the Nordic countries as of today and to look into the development over the past 8–10 years. The level of I/I-water of 2015/2016/2017 was calculated and compared to the 2008/2009 figures which will give an indication whether or not the measures that have been taken to reduce I/I-water since 2008/2009 have had any effect. Some of the same treatment plants that was analysed by Lindholm et al. [4,5] have been re-examined, with data from 2015/2016/2017. This study also includes some simple investigations on how the I/I-water, calculated in the first part, is correlated to rainfall. When trying to reduce I/I-water, it is assumed that large economical investments have to be made. Looking at the development of I/I-water over the past ten years may give some indications on whether or not the investments with the aim to reduce the amounts have had any effect.

Despite the uncertainty related to calculating the amount of I/I-water in both the dilution method and the water balance method, both these methods are used in this study.

2. Materials and Methods

2.1. Study Area

This study makes a follow up of the wastewater treatment plants that were studied by Lindholm and Bjerkholt and Lindholm et al. [4,5]. Wastewater treatment plants in Norway, Sweden, Denmark and Finland have been investigated. In addition, three municipalities in Norway have been more closely examined, Asker (ca 60,000 inhabitants), Bærum (ca 126,000 inhabitants), and Drammen (ca 69,000 inhabitants) [19]. Asker, Bærum, and Drammen are three of the most populated municipalities in Norway.

The study area is shown in Figure 1. In Table 2 the investigated plants are listed.

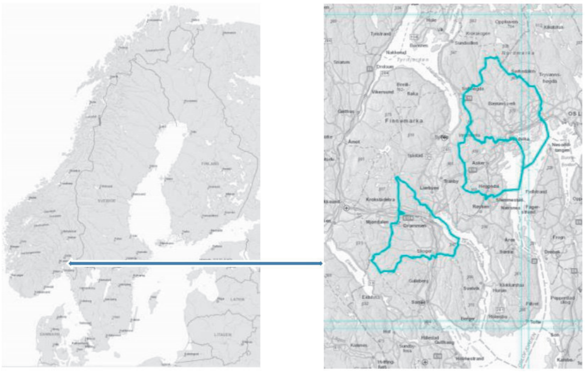

Figure 1. Map of the Nordic countries and a zoom-in of Asker, Bærum, and Drammen municipalities [10].

Table 2. Norwegian, Danish, and Swedish plants included in the I/I-water analysis performed on the years 2009 and 2015/2016/2017.

Norwegian Plants 2009–2017	Danish Plants 2009–2016	Swedish Plants 2009–2015
VEAS	Esbjerg Vest/Spildevand AS	Henriksdal, Stockholm
Bekkelaget Oslo	Frederikshavn Spildevand AS	Ryaverket, Göteborgsregionen
Solumstrand Drammen	Herning Band AS	Käppala, NO Stockholm
Saulekilen Areandal	Horsens and AS	Sjölundverket, Malmö
Lillehammer	Randers Spildevand AS	Bromma, Stockholm
Moss-Kambo	Ringsted Spildevand AS	Nykvarnsverket, Lindköping
Sandefjord	Vandcenter Syd AS	Slottshagen, Norrköping
Tønsberg	Vestforsyning Spildevand AS	Kungsängsverket, Uppsala
Nordre Follo	Aalborg Vest/Kloak AS	Kungsängens ARV, Västerås
Knappen Bergen	Aarhus Vand AS	Duvbackens ARV, Gävle
Ytre Sandviken Bergen		Källbyverket, Lund
Sentralrenseanlegget NJ		Ekeby ARV, Eskilstuna
HIAS		
Alvim Sarpsborg		
Knarrdalstrand Porsgrunn		

For Finland, the calculations have been done by the Finnish Water Utilities Association (FIWA) for Finnish districts from 2010 until 2016. These results are an average of 68 plants that report to FIWA.

2.2. Calculation Methods and the Amount of I/I-Water

The dilution method is based on the assumption that every person produces a certain amount of TOT-P per day and a certain amount of wastewater per day [4]. The higher the average concentration of TOT-P into the treatment plant, the smaller the amount of I/I-water into the same plant.

With the dilution method, the amount of I/I-water for each treatment plant is calculated according to the formula (1).

$$\text{Amount of I/I} - \text{water } (\%) = \left(1 - (c_i)/\left(P_{pd}/Q_{ap}\right)\right) \times 100 \tag{1}$$

where:

I/I = I/I-water in the plant, %
P_{pd} = produced phosphorus (TOT-P) per person and day, mg/pe day
c_i = concentration of Tot-P into the plant, mg/L
Q_{ap} = amount of wastewater produced per person per day, L/pe day

The water balance method is based on the assumption that every person produces a certain amount of wastewater per day.

With the water balance method, the amount of I/I-water is calculated according to the formula (2).

$$\text{Amount of I/I} - \text{water } (\%) = \left(Q_{tot} - pe \times Q_{ap}\right) / Q_{tot}) \times 100 \quad (2)$$

where:

I/I = I/I-water in the wastewater system (%)
Q_{tot} = total amount of water being transported to the measuring point, L/day
pe = the number of persons situated within the catchment area
Q_{ap} = the amount of wastewater each person produces a day, L/pe day

2.3. Norwegian Wastewater Districts

The contents of I/I-water in the Norwegian plants have been calculated based on the concentrations of registered TOT-P. The dilution method has been used in these calculations. The numbers on TOT-P have been provided by the Environmental Agency in Norway [20].

For Norway in general, 18% of the sewers are combined systems. For the systems included in this work, 26% were combined systems [21].

2.3.1. Asker and Bærum Municipalities

In both Asker and Bærum municipalities, almost all houses are connected to the public wastewater system. The wastewater is transported to the wastewater treatment plant VEAS (Vestfjorden Avløpsselskap AS) via a large tunnel. The wastewater system is divided into different zones, and each zone has a measuring point that registers the volume of wastewater transported into the plant. To calculate the amount of I/I–water, figures of measured discharge and number of inhabitants [22,23] were used when applying the water balance method. No corrections have been carried out when it comes to households not connected to the public sewer system. No corrections have been done regarding industry or commuting of people in and out of the districts, as they are both regarded as negligible. The wastewater system in Asker is 100% a separate system, and in Bærum the percentage of combined system/separate system is 35/65 [24].

2.3.2. Drammen Municipality

The wastewater system in Drammen is divided into two districts with separate treatment plants, which of only one, the Solumstrand district, is included in this study. The municipality of Drammen annually produces a report to meet the demands of the County Governor [25]. The annual report presents, among other things, the volume of wastewater delivered to the treatment plant, treated amounts of water in the plant, overflow emissions, and figures on person equivalents (pe) [26,27]. In the calculations done in this study, reported figures for Solumstrand treatment plants have been used. For Solumstrand, commuting is not considered, but industries are included. In the reports to the County Governor, the same figures on pe for all of the considered years are given. Because of this, there are some uncertainties related to these figures. The Solumstrand wastewater district has 56% combined sewers. For the Solumstrand district, I/I-water was calculated using both the dilution method and the water balance method.

2.4. Danish Wastewater Districts

For Danish plants/districts, figures of discharge have been collected from DANVA's (Dansk Vand-og Spildevandsforening; the Danish water and wastewater association) annual reports [28]. In these reports, figures on total organic load, given as pe, are specified. The amount of I/I-water for 2010 and 2016 was calculated using the water balance method.

DANVA specifies that the water consumption in 2016 on an average was approximately 62.67 m^3/pe per year or 172 L/pe per day. One hundred and four liters (104 L) were used by the households. In 2016, the water loss through leakages was about 5 m^3/day. This gives an actual consumption on 158 L/pe per day, or 58 m^3/pe per year. The total water consumption in 2010 was approximately 68.16 m^3/pe per year, including household consumption, industry and institutional consumption and loss of water from the drinking water supply (all water not accounted for are regarded as loss). Without the water loss, the consumption was about 63 m^3/pe per year.

Lindholm et al. [5] calculated the I/I-water using the average volume delivered to a selection of the biggest wastewater plants (277 L/pe per day) minus an average of the produced water in the waterworks. This gave an amount of I/I-water of 91 L/pe per day, or an average of 33%. In this work, the given number of pe was used, together with figures on water consumption.

2.5. Finnish Wastewater Districts

Calculations of I/I-water in Finland are based on figures from the PI system VENLA. The share of I/I-water is calculated using figures of water consumption and water transported into the wastewater plants. The PI-system VENLA is administrated by FIWA. The resulting numbers are a result of an average of 68 waterworks [29].

2.6. Swedish Wastewater Districts

The figures used in the calculations of I/I-water for Swedish plants are obtained from Svenskt Vatten (the Swedish Water and Wastewater Association) [30]. For 2009, the I/I-water for Swedish plants was calculated using the dilution method [5]. In 2017, I/I-water has been calculated using the water balance method on reported values of delivered sewage into the wastewater plants and figures on produced waste water per person. Svenskt Vatten reports that produced wastewater per person corresponds to water consumption and that there are little uncertainty with these figures as all homes are fitted with a water meter [31]. Svenskt Vatten reports that the household consumption in 2015 was 128 L/pe and day. When including industry, the consumption was 183 L/pe and day [32].

In Table 3, a summary of all figures and sources of information, and calculation methods, are given.

Table 3. Summary of values used in the calculation of I/I-water for the year 2015/2016 concerning water consumption, phosphorus production, and the calculation method.

Prerequisite for Calculations Done for the Years 2015 and 2016				
County/Municipality	**Water Consumption (L/pe Day)**	**Source of Information**	**Total Production of Phosphorus (mg TOT-P/pe Day)**	**Method of Calculation I/I-Water**
Norway	140	Literature	1.8	DM
Asker	140	Literature		WBM
Bærum	140	Literature		WBM
Drammen (Solumstrand)	140	Literature		WBM
Drammen (Solumstrand)	140	Literature	1.8	DM
Denmark	158	DANVA		WBM
Finland	140	Norconsult (2014)		WBM
Sweden	183	Svenskt Vatten		WBM

DM, dilution method; WBM, water balance method.

2.7. Data of Precipitation

The Norwegian Meteorological Institute (MET) runs a large number of weather stations, and monitors the weather and climate continuously. These stations measure rainfall among many other parameters. MET also operates stations in Asker, Bærum and Drammen. The total amounts of rainfall have been downloaded from the MET's web site [33]. Likewise, data for Denmark and Sweden have been collected from the Danish (DMI) and Swedish (SMHI) Meteorological institutions, respectively [34,35].

Precipitation is varying a lot both spatially and temporally. On 6 August 2016, a heavy thunderstorm came in over large parts of eastern Norway. Western parts of Oslo, Bærum, and Asker were especially badly hit. In addition to MET's weather stations in Asker, Asker municipality is running four rain gauges on their own. These four gauges recorded a total amount of rain between 48.2 and 55.5 mm over a period of 120 min [36]. Even though the rain may vary a lot over short distances, one gauge is normally representing larger areas due to the costs of instalment and maintenance. When analysing rainfall and amounts of I/I-water for the chosen districts, one should take uncertainty into consideration. Table 4 gives the location of the rain gauges that have been used in the calculations.

Table 4. Districts where figures of rainfall for 2003/2010–2016 have been collected.

Area	Country	Station Name	Source of Information	Data
Asker	Norway	Sem	MET	2003–2016
Bærum	Norway	Horni	MET	2003–2016
Solumstrand	Norway	Berskog	MET	2009–2016
Esbjerg vest	Denmark	Vestjylland	DMI	2009–2016
Randers	Denmark	Østjylland	DMI	2003–2016
Henriksdal	Sweden	Stockholm	SMHI	2009–2016
Ryaverket	Sweden	Göteborg	SMHI	2009–2016
Sjölundaverket	Sweden	Malmö	SMHI	2009–2016

3. Results and Discussions

3.1. Development of I/I-Water in Norway

Inlet concentration of TOT-P is varying a lot in the WWTP in Norway, leading to a large variation in the calculated volumes of I/I-water. Table 5 sums up the measured concentrations of TOT-P and the calculated percentages of I/I-water in the same plants.

Table 5. Measured amounts of TOT-P and calculated percentages of I/I-water for wastewater plants in Norway for 2008 and 2016.

Plant	TOT-P 2008	% I/I 2008	TOT-P 2016	% I/I 20016	Difference % I/I
VEAS	3.66	68	3.53	73	+5
Bekkelaget Oslo	3.62	68	3.81	70	+2
Solumstrand Drammen	3.06	73	3.06	76	+3
Saulekilen Areandal	2.50	78	3.80	70	−8
Lillehammer	4.54	60	6.48	50	−10
Moss-Kambo	4.2	63	5.72	56	−7
Sandefjord	2.47	78	2.79	78	0
Tønsberg	4.11	64	4.10	68	+4
Nordre Follo	4.22	63	5.26	59	−4
Knappen Bergen	2.41	79	4.30	67	−12
Ytre Sandviken Bergen	1.58	86	3.00	77	−9
Sentralrenseanlegg NJ	3.17	72	3.81	70	−2
HIAS	6.87	39	8.31	35	−4
Alvim	3.04	73	4.10	68	−5
Knarrdalstrand	1.63	86	2.71	79	−7

In many of the districts, there has been a positive development. Arendal, Lillehammer, Kambo, Nordre Follo, Knappen, Ytre Sandviken, Alvim, and Knarrdalstrand all have more than a 5% reduction in I/I-water. In a few districts, the development is going in the wrong direction; this goes for VEAS, Solumstrand, and Tønsberg. The average percentage of I/I-water in some big WWTP in Norway suggests that the amounts of I/I-water have been reduced from 70% to 66%.

3.1.1. Asker and Bærum

Volumes (m^3 water/year) of wastewater reaching the treatment plant VEAS from Asker and Bærum varies between years. This variation is shown in Figure 2.

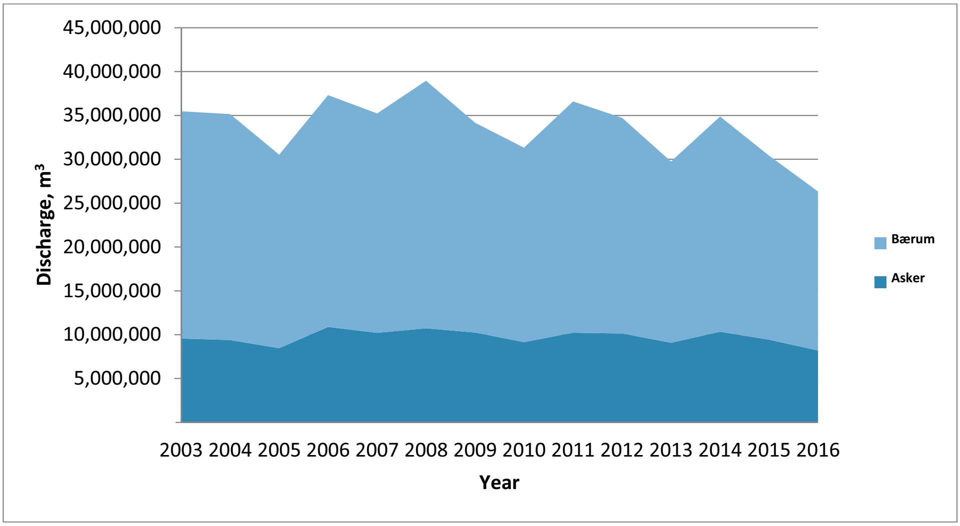

Figure 2. Wastewater from Asker and Bærum delivered to VEAS for the years 2003–2016.

The water balance method has been used to calculate I/I-water in Asker and Bærum municipalities. The results of the calculations are shown in Table 6.

Table 6. Calculated volumes of I/I-water in Asker and Bærum for 2008 and 2016.

Input	Asker		Bærum	
	2008	**2016**	**2008**	**2016**
Discharge, m^3/year	10,719,307	8,191,559	28,239,000	18,134,684
pe	52,922	60,106	110,000	124,000
I/I-water, m^3/år	7,628,662	5,120,142	21,669,000	11,564,684
I/I-water %	71	63	77	64

The trend lines for the two periods (2000–2008/2008–2016) are shown for both municipalities in Figures 3 and 4.

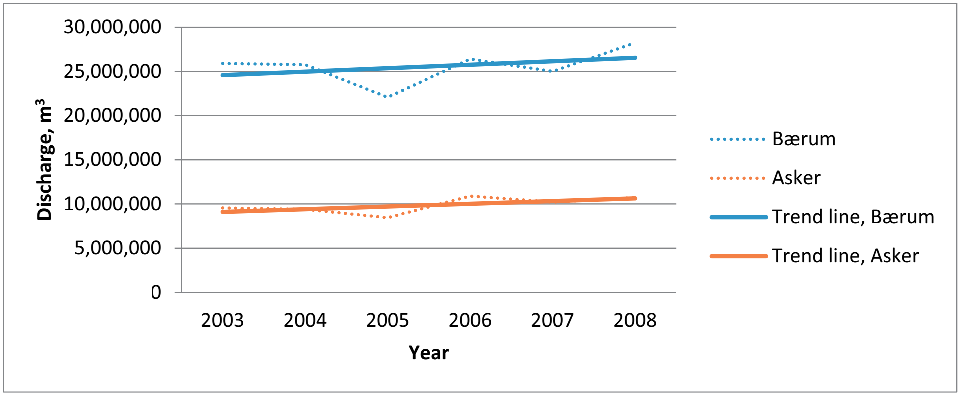

Figure 3. Development of I/I-water in the Asker and Bærum municipalities for 2003–2008.

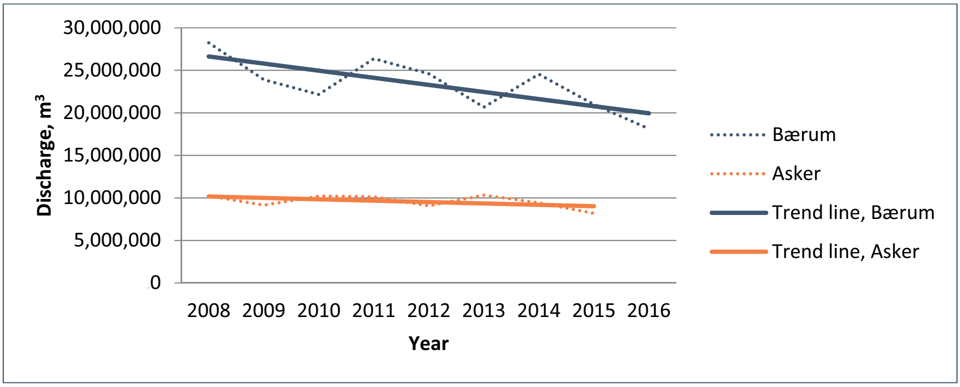

Figure 4. Development of I/I-water in Asker and Bærum municipalities for 2008–2016.

The analysis shows that there is a reduction in I/I-water from 2008 to 2016. However, looking at the broader picture, including all years back to 2003, we see that 2005 and 2016 is almost at the same level. The general trend, though, seems to have changed around 2008 whereas before that, the trend was increasing I/I-water and after 2008 the trend is decreasing I/I-water.

3.1.2. Drammen (Solumstrand)

For Solumstrand, the volume of wastewater transported to the plant and the volume of wastewater overflow comprise the total volume of wastewater included in the calculations for all years from 2009 to 2016. The results of these calculations are shown in Figure 5 and Table 7.

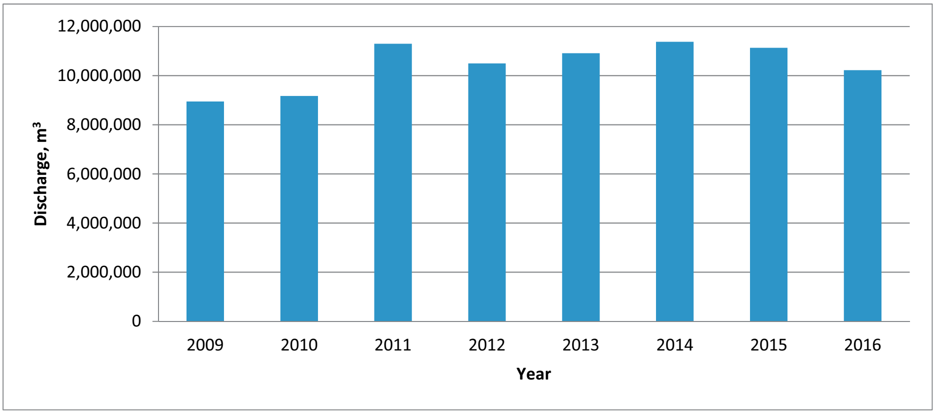

Figure 5. Discharge from the Solumstrand wastewater district for the years 2009–2016.

Table 7. Calculated volumes of I/I water in Drammen with the water balance method and the dilution method for 2008 and 2016.

Method of Calculation	The Water Balance Method		Method of Calculation	The Dilution Method	
Year	2009	2016	Year	2009	2016
Amounts of water, m^3/year	8,947,000	10,219,100	TOT-P, mg/L	3.06	3.06
pe	66,857	66,857	pe	66,857	66,857
I/I-water, m^3/year	5,042,551	6,802,707	Water use, L/pe day	160	140
I/I-water, %	56	67	I/I-water, %	73	76

Calculations of I/I-water using both methods indicate a slight difference in the results. Calculations using the WBM generally give lower values of I/I-water than calculations using the DM. This supports the conclusions of Vråle [2]. The reason why Vråle prefers the DM is that wastewater during heavy rainfall may be transported through weirs to the recipients instead of being transported to the measuringpoint [2]. If the WBM is being used to calculate the amount of I/I-water, water being transported through weirs will contribute to an underestimation of the amount of I/I-water.

However, regardless of what method being used, the development of Solumstrand is going in the wrong direction, showing an increase in I/I-water from 2009 to 2016.

3.2. Development of I/I-Water in Denmark

For calculations of I/I-water volumes for the selected wastewater districts in Denmark, the water balance method was used. The results are shown in Tables 8 and 9.

Table 8. Numbers of pe, discharge and percentage of I/I-water for some investigated Danish wastewater districts for 2010 and 2016.

District	2010			2016		
	pe	Discharge, m^3/year	I/I, %, 2010	pe	Discharge, m^3/år	I/I, %, 2016
Esbjerg Forsyning AS/ Esbjerg Spildevand AS	247,000	17,200,000	10	198,459	16,382,527	30
Frederikshavn Spildevand AS	131,505	11,992,715	31	261,852	11,009,047	−38
Herning Vand AS	126,731	11,181,496	29	217,364	13,260,265	5
Horsens Vand AS	278,981	12,392,123	−42	352,256	12,556,405	−63
Randers Spildevand AS	82,835	10,248,558	49	97,759	10,954,416	48
Ringsted Spildevand AS	88,000	6,082,831	9	92,457	6,006,000	11
Vandcenter Syd AS	383,856	32,828,718	26	328,624	33,703,981	43
Vestforsyning Spildvand AS	142,325	6,413,873	−40	151,361	7,235,948	−21
Aalborg Forsyning AS	195,983	25,130,328	65	344,626	27,166,631	26
Aarhus Vand AS	438,859	35,683,457	23	460,428	37,206,925	28

Table 9. Calculated average values of I/I-water for some big Danish wastewater districts for 2010 and 2016.

Year	2010	2016
Discharge, m^3/year	139,450,478	144,680,745
pe	1,563,264	1,739,718
I/I-water, m^3/year	40,964,846	43,777,101
I/-water, %	29	30

Obvious wrong values have been removed when average values for Denmark of I/I-water have been calculated. This goes for Frederikshavn Spildevand AS, Horsens Vand AS, and Vestforsyning Spildvand AS.

The calculations show that the volumes of I/I-water for the selected Danish wastewater districts have been relatively stable from 2010 to 2016 on about 30%.

DANVA has made some calculation regarding I/I-water related to wastewater systems (combined versus separate) for those districts that are a part of DANVA's benchmarking system [37]. DANVA has calculated the amounts of I/I-water based on measured volumes of wastewater into the wastewater plants and figures on delivered drinking water. Most plants receive approximately 2.5 to 3 m^3 of wastewater to each m^3 of drinking water produced. In these plants, there is about 70% separate systems [37]. A ratio of 2.5 of wastewater to drinking water represents a fraction of I/I-water of approximately 60%. Considering this and the calculations made in this work shown in Table 9, indicates that the variations of I/I-water between the districts in Denmark are relatively large. The analysis performed by DANVA shows a variation in I/I-water between 40% and 80%. The results from DANVA indicate that the calculation done in this study, and the study done by Lindholm et al. [5], gives an I/I-water ratio that is too low. This may be due to the selection of the average value used in the calculations. Another possibility is that methods of calculating the I/I-water are inadequate.

3.3. Development of I/I-Water in Finland

The Finnish organization FIWA (Finnish Water Utilities Association) has analysed the average amount of I/I-water for 68 waterworks in Finland for 2016. The fraction of I/I-water was 40.8%. About 95% of all wastewater systems in Finland are separate systems [29]. The Finnish calculations are shown in Figure 6.

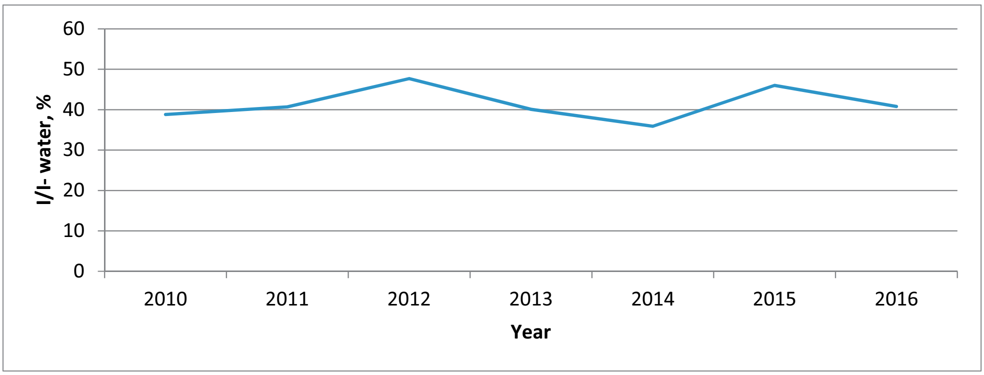

Figure 6. The development of I/I-water in Finland from 2010 to 2016 [26].

3.4. Development of I/I-Water in Sweden

I/I-water volumes into some big wastewater plants in Sweden have been calculated by using the water balance method. The results of the calculations are shown in Tables 10 and 11.

Table 10. Calculation of I/I-water for some big Swedish wastewater plants for 2009 and 2015 based on values of discharge and specific values of produced wastewater.

Wastewater District	I/I, %, 2009, based on 160 L/pe Day, 1.92 g TOT-P/pe Day	Discharge, 2015, L/pe Day	Produced Wastewater, 2015, L/pe Day	I/I-water, L/pe Day 2015	I/I-Water, %, 2015
Henriksdal, Stockholm	52	348	230	118	34
Ryaverket, Göteborgsregionen	68	500	178	322	64
Käppala, NO Stockholm	65	341	188	153	45
Sjölundverket, Malmö	59	355	226	129	36
Bromma, Stockholm	77	423	237	186	44
Nykvarnsverket, Lindköping	27	65	234	−169	−260
Slottshagen, Norrköping	49	320	169	151	47
Kungsängsverket, Uppsala	47	286	213	73	26
Kungsängens ARV, Västerås	58	377	211	166	44
Duvbackens ARV, Gävle	73	387	0	387	100
Ekeby ARV, Eskilstuna	73	548	220	328	60

Table 11. Calculated values of I/I-water for some big Swedish plants for 2010 and 2015.

Year	2010	2015
pe	247,481	373,111
I/I-water, %	58	46

Obvious wrong numbers have been removed when the average value of I/I-water has been calculated for 2015. This goes for Nykvarnsverket (−260% I/I-water) and Duvbackens ARV (100% I/I-water).

For the Swedish plants included in this study, a reduction in I/I-water volumes from 2010 to 2015 are observed. The calculations show a reduction from 58% to 46%.

Annually, Svenskt Vatten produces the report "Resultatrapport för VASS Drift" (a report with results regarding wastewater and water services). This report sums up the results for the Swedish benchmarking regarding water and wastewater services [32]. For 2015, the report gives an average value of produced wastewater of 183 L/pe per day. Using this figure, the analysis gives an average of 58% of I/I-water when removing clearly incorrect input data.

3.5. I/I-Water and Gauged Rainfall

Comparisons of the volumes of wastewater delivered to the WWTP and gauged rainfall for Asker, Bærum, and Drammen in Norway, and the districts Esbjerg vest and Randers in Denmark, are shown in Figures 7 and 8.

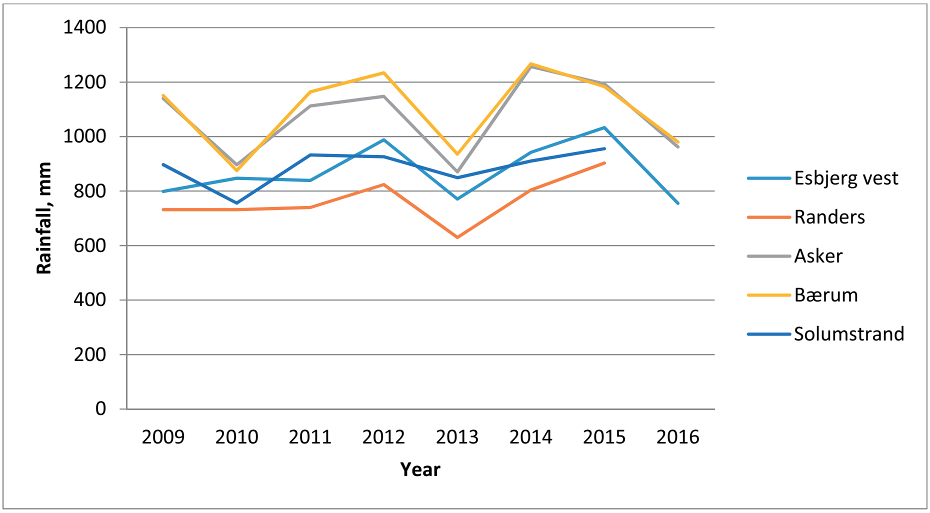

Figure 7. Rainfall in Asker, Bærum, Drammen, Randers, and Esbjerg vest.

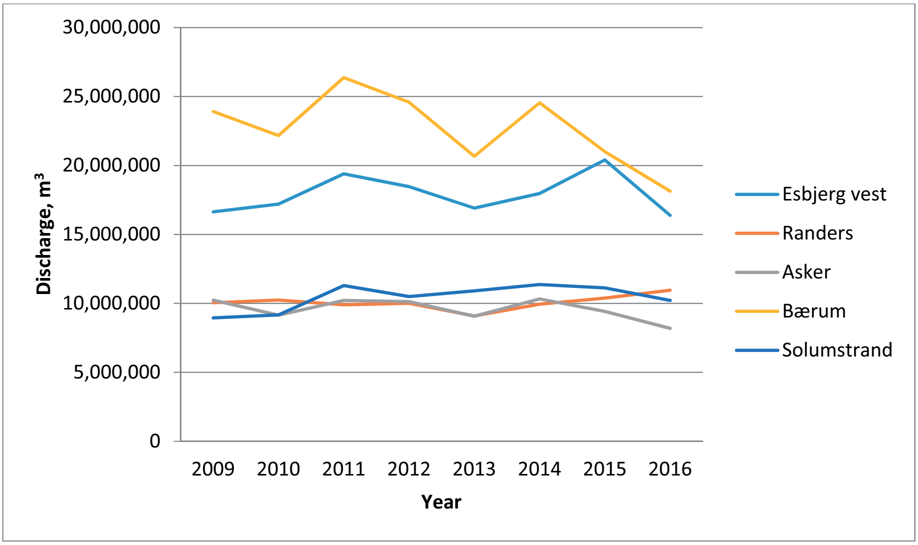

Figure 8. Discharge in Asker, Bærum, Drammen, Randers, and Esbjerg vest.

Clearly, it rains more in Asker and Bærum than in Drammen and the two locations in Denmark. Also, the volumes of wastewater delivered to the plants are much bigger in Asker and Bærum than for the other three locations. 2013 was a dry year for all the locations, and also all the locations, except for Drammen, were at a minimum regarding discharge in 2013.

Using linear regression, the discharge has been correlated to rainfall for the five locations. The result of the regression-analyses is shown in Table 12.

Table 12. Results from a linear regression analysis between rainfall and discharge for Asker, Bærum, Drammen, Randers, and Esbjerg vest.

Location	Nr of Observations	R^2	p-Value
Asker	8	0.534	0.039
Bærum	8	0.389	0.098
Drammen, Solumstrand	8	0.302	0.158
Randers	8	0.316	0.147
Esbjerg vest	8	0.616	0.021

The results show a correlation between rainfall and discharge in Asker and Esbjerg vest. It needs to be pointed out that the number of observations may be a bit too low to draw complete conclusions.

Table 13 sums up the calculated values of I/I water for 2015/2016 together with the percentage of combined system and average amounts of rainfall for all investigated areas.

Table 13. Summary of results of studies on the Nordic countries of I/I-water in the wastewater systems for the years 2015/2016.

County	Average Values of I/I-Water in 2015/2016			
	I/I-Water, %	% with Combined System	Gaged Rainfall in 2016, mm	Comment
Investigated plants in Norway	66	26 (2017)		DM
Asker	63	0 (2017)	963	WBM
Bærum	64	35 (2017)	940	WBM
Drammen (Solumstrand)	67	56 (2017)	778	WBM
Drammen (Solumstrand)	76	56 (2017)	778	DM
Denmark	30	Ca 50 (2012)		WBM
Denmark	40–80	Ca 30 (2017)		Calculations done by DANVA
Esbjerg vest	30		755	DM
Randers	48		764	DM
Finland	41	5 (2017)		Calculations done by FIWA
Sweden	46	15–20 (2012)		WBM
Sweden	49	15–20 (2012)		Calculations done by Svenskt Vatten
Henriksdal, Stockholm	34		656	WBM
Ryaverket, Göteborgs-regionen	64		1065	WBM
Sjölundverket, Malmö	36		789	WBM

4. Conclusions

For wastewater treatment plants in Norway, there have been small but positive changes regarding volumes of I/I-water from 2008 to 2016. The average value for the studied plants in 2016 was 66%, while analysis using 2009 data shows an average of 70%. For most of the Norwegian plants, I/I-volumes are decreasing, but for a few districts, the opposite is the case.

Analysis of the data for Asker and Bærum municipalities in Norway is indicating a positive development regarding I/I-water when relating I/I-water to rainfall for all years from 2003 up until today. The volumes of I/I-water are decreasing despite an increase in rainfall.

For the Solumstrand district in Drammen, Norway, the development in I/I-water is going in the wrong direction, increasing from 2009 to 2016. Part of the explanation for Drammen developing negatively compared to Asker and Bærum may be the differences in the share of combined systems, which is higher in Drammen than the two other municipalities, 56% in relation to 0% and 35%.

Using both the dilution method and the water balance method on the Solumstrand data gives a difference in the results. Calculations using the dilution method give higher volumes of I/I-water compared to the water balance method. Looking at the inputs for these two methods, it is likely that the dilution method is giving a more correct picture of the situation than the water balance method. This is due to the fact that water leaves the system through overflows along the pipes in most wastewater systems, and this is difficult to take into account when using the water balance method.

DANVA's analysis shows that the amount of I/I-water in Denmark varies between 40% and 80%. The analysis performed in this study using data from 2016 shows an average value of I/I-water on 30%. The calculated average values using data from 2009 and 2016 are probably underestimating the I/I-water fraction. There are some indications that the selected samples are not representative of all wastewater districts in Denmark.

FIWA reports that the amount of I/I-water in Finland in 2016 was 40.9%. This is an increase compared to the analysis done by Lindholm et al. using the 2009 data, where they found the I/I-water fraction to be 29%. The 2012 result was probably underestimating the situation. This may be a result of not using a representative selection of WWTP in 2012, or the fact that different calculation methods were used.

Svenskt Vatten has calculated the average fraction of I/I-water in Sweden to be about 49% in 2012. Calculations performed by Lindholm et al. show a fraction of I/I-water of 58% for 2009. The analysis performed in this study, for the same plants investigated by Lindholm et al., gives an average of 46% for 2015. For three examined districts in Sweden, the percentage of I/I-water varies between 34, 64, and 36 in 2015. In 2009, the figures of I/I-water in the same districts were 52, 68, and 59. The amounts of I/I-water have decreased in all three districts.

In this study, Denmark is the country with the lowest fraction of I/I-water. This may be a result of the uncertainties associated with the water balance method, which was used in the calculations regarding Denmark, but may also be a result of the locations in Denmark receiving less rain than the Norwegian and Swedish locations.

Calculated amounts of I/I-water will depend on estimated water consumption per capita in the districts. It will also be of importance to what extent the water consumption has been measured or only stipulated. Correct values on total volumes of wastewater in each district, and volumes of wastewater leaving the system through overflow weirs, are also crucial if the water balance method is to be used.

Rainfall will influence the amounts of I/I-water in some wastewater districts. To be able to look at long-term development in I/I-water, it is, therefore, of importance to compare the results with data of rainfall. It is also important to look into long series of data. Year-to-year comparisons are not recommended.

There are some uncertainties related to the results derived through this study. These uncertainties are associated to assumptions made on water consumption, wastewater being transported away from the system through weirs, production of Phosphorous, measured amounts of TOT-P, number of inhabitants, water use in industry, commuting, and exact amounts of rainfall. If this study had been conducted on a smaller area, it would be easier to control most of the variables listed above. If one in addition could control the level of I/I-water with other parameters than TOT-P it probably would be possible to know how dilute the wastewater is without making calculations and assumptions. Such sensors are still not commonly used in the wastewater piping system, but it is likely to believe that they will be in the near future. Sensors installed locally will improve the possibilities for finding locations where the I/I-water enters the wastewater system.

Through this study, some of the influencing factors regarding I/I-water in wastewater systems have been identified. In this study only rainfall and system solution (combined/separate) were included. Other factors of importance may be the age of the sewer pipes and leakages from the drinking water pipes. To efficiently reduce the volume of I/I-water, it is important to investigate what factors that affect the I/I-water the most. It is also important to relate different field parameters, such as the level of the groundwater table, urbanization and impervious surfaces to the amount of I/I-water. Further investigations should therefore include more variables in order to be able to conclude which parameters are the most important influencers regarding the level of I/I-water.

Author Contributions: Conceptualization, K.J.S.; Investigation, K.J.S.; Project administration, K.J.S.; Supervision, J.T.B. and O.G.L.; Writing—original draft, K.J.S.; Writing—review & editing, J.T.B., O.G.L., and H.R.

Funding: The authors want thank Asker municipality and the Research Council of Norway for financing this study.

Acknowledgments: The authors want to thank Asker, Bærum and Drammen municipalities, DAVA, Svenskt Vatten and FIWA for willingly sharing information and for giving access to data. In addition the authors want to thank the Norwegian Environment Agency for granting access to WWTP data.

Conflicts of Interest: The authors declare no conflict of interest.

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Identifying factors influencing Infiltration and Inflow-water (I/I-water) in wastewater systems using multivariate data analysis

Av Kristin Jenssen Sola, Knut Kvaal, Jarle T. Bjerkholt, Oddvar G. Lindholm and Harsha Ratnaweera

Kristin Jenssen Sola is civil engineer at Asker municipality and Ph.D candidate at NMBU
Knut Kvaal is professor emeritus at NMBU
Jarle T. Bjerkholt is a professor and deputy vice-chancellor at the University of South-Eastern Norway
Oddvar G. Lindholm is professor emeritus at NMBU
Harsha Ratnaweera is Dr. ing. and professor at NMBU

Summary

The share of infiltration and inflow water (I/I-water) in the wastewater network is influenced by several factors. The purpose of this study is to propose a method to investigate the relationship between different variables and the proportion of I/I-water in the wastewater network. The method tested is a multivariate modelling technique with which the following variables were examined; a) estimated water leakage from drinking water pipes, b) total volume of delivered drinking water, c) average age of the sewer pipes, d) renewed amounts of sewer pipes, e) system solution (share of combined system) and f) precipitation. The multivariate modelling analysis reveals different patterns in influencing factors. When using the proposed model it is possible to rank the variables included in the model and the optimal level of I/I-water should be determined after identifying the factors influencing the I/I-water. When aiming to remove I/I-water the most cost-efficient measures should be considered. These measures may vary according to context.

Sammendrag

Bruk av multivariat analyse som verktøy for å identifisere ulike påvirkningsfaktorer til fremmedvann i avløpssystemet. Fremmedvannsnivået i avløpsnettet påvirkes av flere ulike faktorer. Hensikten med denne studien har vært å undersøke hvorvidt bruk av multivariat analyse kan være en egnet metode for å finne sammenhenger mellom fremmedvann og ulike variable. De undersøkte variablene er a) drikkevannslekkasjer, b) andel levert drikkevann, c) gjennomsnittsalder på avløpsnettet, d) andel fornyet avløpsnett, e) andel fellessystem og f) nedbør. Ved hjelp av multivariat analysen har det blitt funnet ulike mønstre når det gjelder påvirkningsfaktorer til fremmedvann. Ved hjelp av den etablerte modellen er det mulig å rangere variablene som har vært inkludert i analysen. Det optimale fremmedvannsnivået bør settes etter at ulike påvirkningsfaktorer til fremmedvann er blitt identifisert. De mest kostnadseffektive tiltakene bør vurderes når fremmedvann skal fjernes. Disse tiltakene vil variere fra sted til sted.

Introduction

Leakages from drinking water pipes in Norway are high compared to other European countries. The average percentage of leakage for all Norwegian waterworks was estimated to be about 30% in 2017 (Statistisk Sentrabyrå (SSB), 2018a). In Norway, 50% of leakages from drinking water are traditionally presumed to end up as I/I-water (Ødegaard et al., 2012). This may be a consequence of the fact that drinking water pipes and wastewater pipes mostly are situated in the same trench. In Norway, a typical pipe trench is constructed as shown in figure 1. A high amount of drinking water leakages may potentially influence the level of I/I-water.

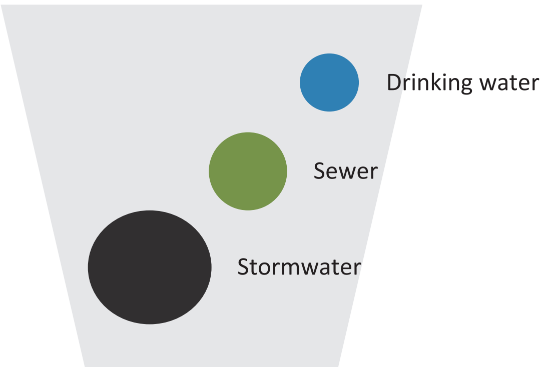

Figure 1. A typical Norwegian pipe trench

If it is indeed the case that drinking water contributes about 50% of I/I-water, this may be an important reason why the share of I/I-water in some areas in Norway is high.

How the groundwater level may influence the amounts of I/I-water is discussed in a study by Franz (2007), who argues that groundwater level is the main contributor to I/I-water. By using Multidimensional Scaling (MDS), Franz investigated which attributes influence the amounts of I/I-water the most. Franz concluded that the groundwater level is essential when characterising two wastewater districts by different attributes in Germany (Franz, 2007). The relationship between I/I-water and groundwater level was also investigated by Karpf and Krebs (2011). They found that both groundwater level and the year of installation of the sewer pipes were of importance regarding amounts of I/I-water (Karpf & Krebs, 2011). Even if the groundwater level is regarded as one of the most important influencing factors on the share of I/I-water, this variable is not included in this study. This is due to the fact that this study is based on Norwegian data and groundwater level is rarely measured in Norwegian wastewater districts.

The data used in this study are extracted from public sources of information, such as reports from the municipalities to the government. The variable *share of combined system* has only been reported from the municipalities to the Norwegian authorities since 2013. Even so, the analysis performed in this study includes this variable.

In 2012 the County Governor of "Oslo and Akershus" sent a request to all municipalities in Oslo and Akershus to mobilize against I/I-water. The County Governor had reason to believe that the level of I/I-water was too high and claimed the maximum acceptable level should be 30%. The level of I/I-water in the municipalities varied between 41% and 74% in 2010 (Fylkesmannen i Oslo og Akershus, 2011). The municipalities in this specific county vary a lot as far as topography and other local conditions are concerned. It is, therefore, reasonable to question if an equal level in all municipalities regarding I/I-water is achievable at a reasonable cost.

Wastewater is frequently divided into various fractions depending on its origin. The total share of I/I-water in the wastewater depends on the individual contribution of each of the components listed below:

- Sewage from households, industry, and institutions
- Drinking water leaking from drinking water pipes
- Groundwater, which is influenced by precipitation and seasons, but still is a relatively constant contribution. This contribution to the I/I-water is a consequence of leaky pipes and manholes
- Infiltrated rainwater. Rainwater also enters the sewer pipes through leaky pipes and

manholes. The share of infiltrated water depends on precipitation which infiltrates into the ground before it enters the sewer system. Groundwater may be a part of this contribution.
- Inflow water as a consequence of faulty connections. Sources may be house drainage, road drainage, unsealed manholes where water enters from the surface or streams connected to the sewer system.

The individual contribution may, for instance, be investigated using a calibrated hydraulic model. This was done in 2013 in a study from Oslo, Norway which correlated the following parameters to the share of I/I-water, I: share of combined system, II: average age of sewer pipes, III share of sealed surfaces, IV: number of crossings between sewer pipes and rivers, V: culverted rivers. The study concludes that the share of I/I-water is highly variable and difficult to predict (Torres, 2013). In 2014 another study was conducted in the Oslo area. In this study, different sources of I/I-water were calculated. The total share of I/I-water was calculated to be about 47%, of which leakages from drinking water pipes contributed with 15%, infiltrated rainwater contributed 75% and groundwater contribution was about 10% (Gammelsæter, 2014).

The contribution of different components to the I/I-water may also be investigated using a multivariate modelling technique. The goal of this study is to examine if such a multivariate modelling technique is a suitable method to identify the variables contributing to I/I-water in different locations. The variables included in this study are:
- estimated water leakages from drinking water pipes
- total volume of delivered drinking water
- average age of the sewer pipes
- rate of renewal of sewer pipes
- system solution (share of combined system)
- annual precipitation

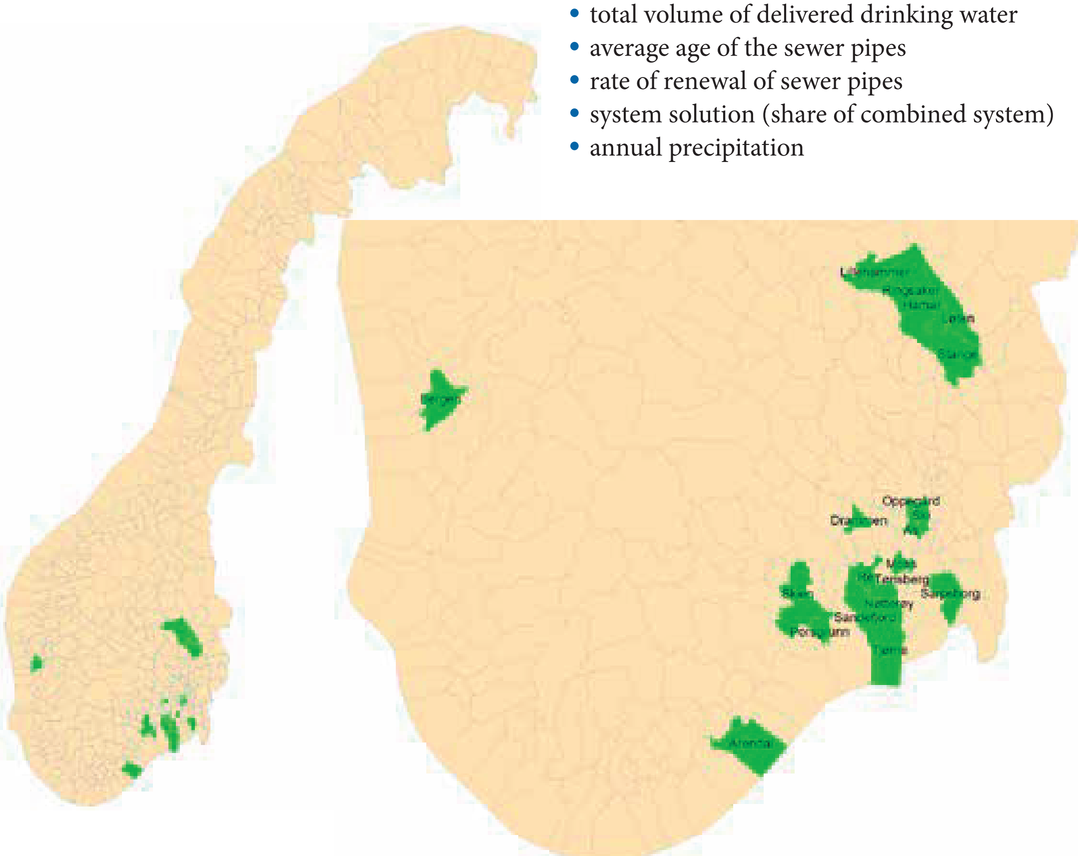

Figure 2. Map of the municipalities connected to the investigated WWTPs (Geodata AS, 2018).

Material and methods

Study area

Lindholm and Bjerkholt (2011) investigated the I/I-water situation for 14 of the largest wastewater treatment plants (WWTPs) in Norway. Of these, 11 WWTPs are further examined in this study. Due to lack of data it was not possible to investigate the remaining three WWTPs. The municipalities that have ownership in the WWTPs are shown in figure 2. The plants are also listed in table 1.

Some of the municipalities have been restructured in the period of the study. In total, about 770,000 persons are connected to the 11 WWTPs investigated in this study (Statistisk Sentrabyrå (Stastistics Norway), 2018) {Statistisk Sentrabyrå (SSB), 2018 #50}.

In addition, the potential contribution from drinking water leakages on the total amount of I/I-water has been examined for Asker municipality.

Data collection and quality

Norwegian municipalities/entities are required by law to make annual reports to the national government on several parameters related to municipal wastewater management/emissions (Lovdata, 2018; Statistisk Sentrabyrå (SSB), 2018b). Some of the reported parameters are collected by KOSTRA (a Norwegian municipality to the Government reporting program) (KOSTRA, 2019). The information on Total-Phosphorus (Tot-P) used in this study was given by the Norwegian Environment Agency (Finnesand, 2017). In addition, data on estimated water leakages, total amounts of drinking water delivered average age of the sewer pipes, total length of renewed sewer pipes as a percentage of the complete system, and the share of combined systems has been collected from the KOSTRA website (KOSTRA, 2019). The municipalities report to the Norwegian Environment Agency and KOSTRA every year, without any further quality control. It is therefore assumed that the quality of the data may vary. Some figures may also be missing for certain years, and are difficult to complement. Precipitation data have been extracted from MET, the Norwegian Meteorological Institute's database eKlima (Meteorologisk institutt (MET)). MET runs a network of weather stations all over Norway and all results are published online.

As mentioned above, the datasets may be incomplete due to incorrect or missing registrations and it has been necessary to do some simplifications and assumptions during this study. This comes as a consequence of one or both of the following facts:

- Some WWTPs included in the investigation may not be connected to the entire

Table 1. Wastewater treatment plants (WWTPs) and rain gauges investigated in the study.

Wastewater treatment plant	Connected municipalities	Rain gauge identity number	Rain gauge name
Kambo (Ka)	Moss	17251	Moss brannstasjon
Alvim (Al)	Sarpsborg	3190	Sarpsborg
Solumstrand (So)	Drammen	26900	Berskog
Sandefjord (Sf)	Sandefjord	27600	Sandefjord
Knardalstrand (Kr)	Porsgrunn, Skien	27600	Sandefjord
Saulekilen (Sau)	Arendal	36200	Torungen fyr
Knappen (Kn)	Bergen	50540	Florida
Lillehammer (L)	Lillehammer	12680	Sætherengen
Tønsberg (Tøn)	Tønsberg, Nøtterøy, Tjøme, Re, Stokke	27270	Kilen
HIAS (Hi)	Hamar, Løten, Ringsaker, Stange	12320	Stavsberg
Nordre Follo (NoF)	Ski, Ås, Oppegård	17850	Ås

wastewater system in a municipal wastewater district.
- Some WWTPs receive effluent from more than one municipality.

In these cases, the average values of the investigated variables have been calculated.

Precipitation may vary significantly over short distances. One must therefore anticipate some uncertainty if relying on data from a single location to represent the precipitation of an entire district. Despite this fact, for the purpose of this study, one station per district was chosen to simplify the analysis.

The potential drinking water contribution to I/I-water has been investigated in five points in Asker municipality. The discharges in the wastewater network have been measured for several years in these points and are considered reliable. In four of the points, the amounts of I/I-water have been calculated based on the number of person equivalents (pe) connected to the point. The investigated period for these four points was the summer of 2018, which was really dry in Asker. In the fifth point the measured discharges in the wastewater pipes have been compared to delivered amounts of drinking water.

In table 2 the selected measuring points in the wastewater network is shown.

Methods

Determination of I/I-water

The share of I/I-water may be calculated using the dilution method (Lindholm & Bjerkholt, 2011). Concentrations on Tot-P into WWTP are considered a measure on how big the share of I/I-water into the same plant is. The amount of I/I-water is calculated according to formula (1) (Jenssen Sola et al., 2018).

$$\text{Amount of I/I-water [\%]} = (1- (ci)/(P_{pd}/ Q_{ap})) \times 100 \qquad (1)$$

Where:
I/I = I/I-water in the plant [%]
P_{pd} = produced phosphorus (TOT-P) per person and day [mg/pe day]
ci = concentration of Tot-P into the plant [mg/l]
Q_{ap} = amount of wastewater produced per person per day [*l*/pe day]

In Norway, a phosphorus production of 1.8 g Tot-P per person per day is commonly used (Lindholm & Bjerkholt, 2011; Ødegaard et al., 2012). In formula (1) both commuting and industry is considered negligible. The amount of wastewater produced per person per day is set to be 140 liters (Jenssen Sola et al., 2018).

When calculating I/I-water in Asker, the water balance method was used according to formula (2) (Jenssen Sola et al., 2018).

$$\text{Amount of I/I-water [\%]} = (Q_{tot} - pe \times Q_{ap})/ Q_{tot}) \times 100 \qquad (2)$$

Where:
I/I = I/I-water in the wastewater system [%]
Q_{tot} = total amount of water being transported to the measuring point [*l*/day]
pe = the number of persons situated within the catchment area
Q_{ap} = the amount of wastewater each person produces per day [*l*/pe day]

Table 2. Selected measuring points in Asker.

Manhole number	Number of connected pe	Method
10286	7530	Discharge and dry weather flow
160376	6140	Discharge and dry weather flow
4666	4666	Discharge and dry weather flow
2600	14003	Discharge and dry weather flow
10268	3200	Discharge and delivered amounts of drinking water

Linear regression

Linear regression was used to investigate the relationship between different variables. One by one the variables were correlated against Tot-P, one location at the time. A 95% confidence interval was used in the regression calculations.

Multivariate data analysis

When investigating several variables (X) simultaneously, and to conduct more explorative analysis, multivariate data analysis is applied. Multivariate analysis is useful to single out which variables are the most important, and what relationships there are between the variables. The Unscrambler 10.5 (Camo Software AS, 2014) was used to perform the calculations in this study.

Principal Component Analysis (PCA) is a method to find hidden data structures and correlations between variables (Esbensen & Swarbrick, 2018). Hidden trends in datasets, which otherwise could be difficult to discover may be revealed (Esbensen & Swarbrick, 2018). When correlations exist between variables in the dataset, PCA performs a dimensional reduction of uncorrelated latent variables that describe the principal directions in the data (Principal Components (PCs)) Several PCs are extracted which all together explains the relationships found in a multivariate dataset (Esbensen & Swarbrick, 2018).

The **Score plot** shows how the samples are related to each other. The **Influence plot** is used when interpreting the PCA and may be used to identify if the dataset is under the influence of possible outliers. If many points are situated in the first quadrant this may indicate that these samples are outliers. **The Correlation Loading plot** shows which variables are significant and how the variables correlate (Camo Software AS, 2014; Esbensen & Swarbrick, 2018). The 2-D plot contains two ellipses that indicate how much variance is taken into account by the model. The outer ellipse is the unit circle and indicates 100% explained variance. The inner ellipse indicates 50% of explained variance. Variables with less than 50% explained variance are candidates to be left out of the analysis.

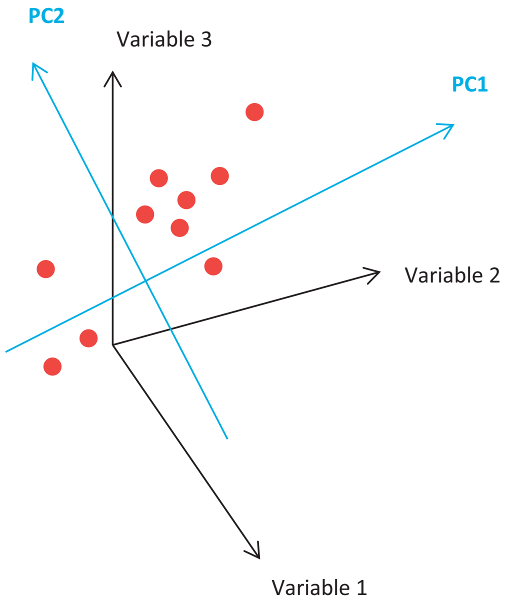

Figure 3. The extracting process of Principal Components from variables (Camo Software AS, 2014).

The extracting process of Principal Components is shown in figure 3. The first PC (PC1) accounts for the direction of highest variation in the data. The second PC (PC2) accounts for the next highest variation normal to PC1 direction and so on. This results in a new coordinate system with the PCs as bases.

The validation process is important when performing statistical analyses. A validation will show how general a model is. Cross-validation is used to screen the modelability of the data. In cases with few samples, cross-validation is used. When many data samples exist, a test set validation is better to use. In our case, we have used cross-validation with samples randomly sorted into blocks. In cross-validation a block of samples is left out and tested against the remaining samples. This procedure is repeated until every block of samples has been left out once (Esbensen & Swarbrick, 2018).

Results

Contribution from drinking water leakages

The summer of 2018 was very dry in Asker. The average precipitation in Asker municipality during June/July/August was 46/22/53 mm respectively (Rosim AS), whereas the average values for the current reference period (1961-1990) are 72/90/106 mm for the same months (YR, 2018). Because of the minor amounts of precipitation, there are reasons to believe that the main sources of I/I-water this summer were leakages from drinking water pipes, inflow from rivers/culverted rivers and possibly groundwater. Since the investigated period was very dry, it is also likely that the groundwater level was low. Even so, it may not be excluded that the measuring points may be influenced by groundwater.

The calculated level of I/I-water is shown along with gauged rainfall for the station "Mellomnes", in figure 4. The level of I/I-water has been calculated using the water balance method.

There is no registered rainfall between 17.06.18 and 09.07.18, and throughout this period the I/I-level decreased for all four points. Even though the I/I-level varies, the level is at a minimum between July 5th and July 8th for all points. In catchment area 10286 there are no obvious intersections between sewer pipes and open/closed streams. For catchment 160376 and 4666 some pipes run along streams and may be

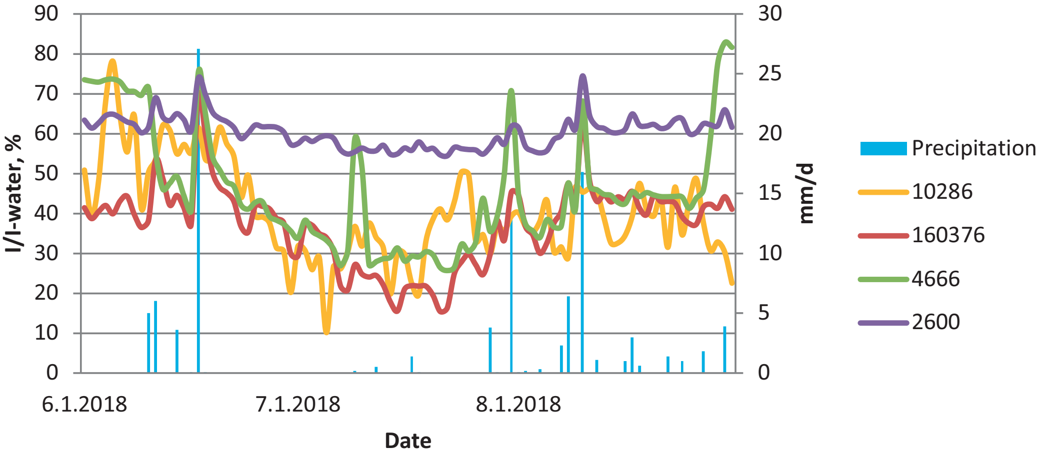

Figure 4. Calculated amounts of I/I-water in four locations/catchment areas, together with gauged rainfall measured at Mellomnes in June, July and August 2018.

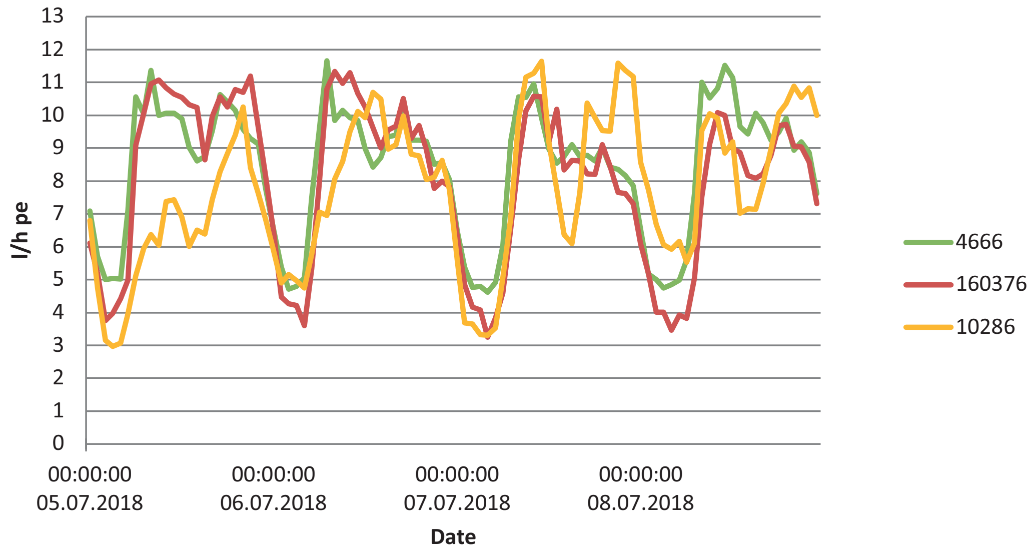

Figure 5. Measured discharge for three catchments between 05.07.-09.07.2018.

Table 3: Extracted and calculated information regarding flow measuring points in Asker municipality on the 05.07.2018-08.07.2018.

Manhole number	Number of connected pe	DWF (l/h pe), Minimum	DWF (l/d pe), Baseflow
10286	7530	3.0	72
160376	6140	3.6	86
4666	1538	4.6	110

influenced by this. In catchment area 2600 the sewer pipes are most likely to be influenced by a river. Due to the measured discharge in point 10286 there is reason to believe that leakages from drinking water pipes contribute to about 10% to 15 % of the total amount of I/I-water.

Figure 5 shows five days from July 5th to 9th when there was no precipitation for about three weeks. Measuring point 2600 is not included in figure 5.

The lowest registered level of discharge is at night-time, from 2 a.m. to 4 a.m. At this point, the dry weather flow (DWF) for 4666 is 4.4 *l*/pe hour, for 160376 it is 3.6 *l*/pe hour and for 10286 the lowest registered level of discharge is 2.3 *l*/pe hour. Table 3 sums up information regarding the three investigated measuring points.

By analysing data from the summer of 2018, we see that leakages from drinking water pipes may contribute to a minimum of 72*l*/d pe of the total discharge in the wastewater network.

On March 18th 2018, there was reported a leakage from a drinking water pipe in Asker. The measured amount of drinking water through one of the flow meters was abnormally high. In the same area a flow meter registered an increase in the measured discharge in a wastewater pipe, despite no registered precipitation during this period. The measured wastewater discharge and measured drinking water consumption is shown in figure 6, together with registered precipitation in station "Mellomnes".

The registered peak in discharge between the 18.03.2018 and the 02.04.2018 (figure 6) is not caused by precipitation, but must come as a consequence of the registered leakages from the drinking water pipe. Just before the pipe was damaged the discharge was about 400 m^3/d and

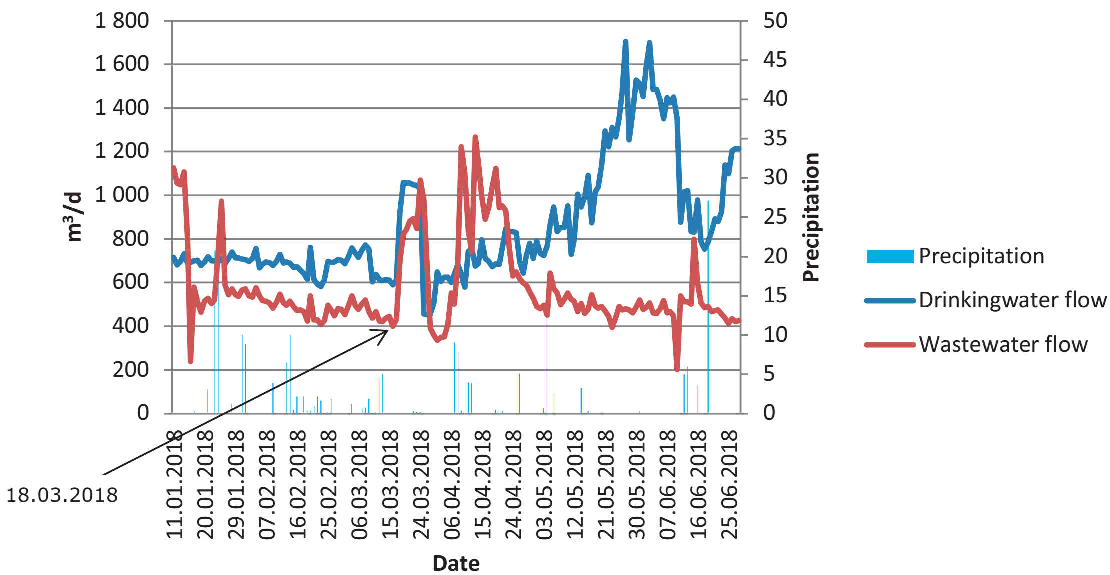

Figure 6. Measured discharge compared to measured drinking water use and precipitation measured at Mellomnes.

Table 4: Changes in measured water flows due to a broken drinking water pipe

Situation	Drinking water flow, m³/d	Wastewater discharge, m³/d
All pipes functioning as normal. Dry weather (not summer). 16.03.2018	590	400
Broken drinking water pipe. Dry weather (not summer). 19.03.2018	1050	820
"Lost" drinking water	460	
Increase in discharge		420

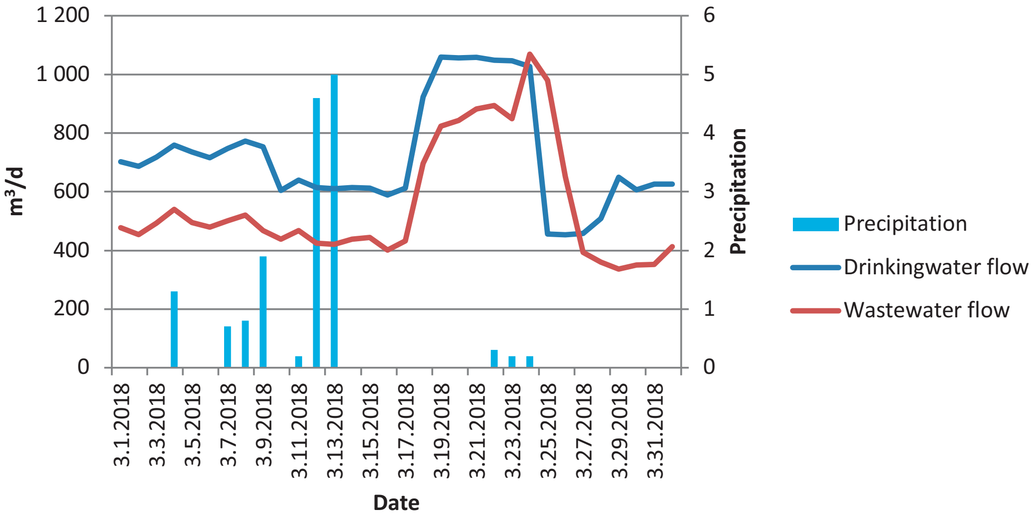

Figure 7. Measured drinking water flow and wastewater flow during a drinking water pipe break.

the water use about 600 m³/d. Both measured water flows peaks about 1100 m³/d.

A close up on the dates from 01.03.2018 to 01.04.2018 is shown in figure 7.

Extracted information from figure 6 and 7 is listed in table 4.

Investigations show that leakages from drinking water pipes contribute to a base flow of I/I-water at approximately 72 *l*/d pe, or a minimum of 10-15% of the total amounts of I/I-water. In the case of a sudden break on a drinking water pipe, as much as 91% of the leakages may be found in the waste water pipes. Drinking water may potentially be a considerable factor in some areas when investigating different sources of I/I-water.

Linear regression

In figure 8 the development of the Tot-P concentration in the investigated WWTP is shown for all locations. Applying the dilution method, Tot-P may be used as a measure of the size of the share of I/I-water. Figure 8 shows that HIAS, Kambo, and Lillehammer have the highest Tot-P values, and therefore also the lowest proportion of I/I-water. Meanwhile, Sandefjord and Knardalstrand appear have the greatest challenges regarding I/I-water.

Results from the regression analysis on Tot-P, on all variables for each location, are shown in table 5. A p-value < 0.05, together with a relatively high r^2 value indicates that a variable may be significant, using a 95% confidence interval. These values are highlighted in green in table 5.

For most of the investigated variables, there is no correlation between any of the variables and the amount of Tot-P. It is difficult to point out one variable that may explain the challenges of I/I-water. When comparing table 5 and figure 8 it is reasonable to assume that the good results

Table 5: Results from a regression analysis performed on each variable for each location in relation to Tot-P. Green colour indicates which variables that may be significant.

WWTP	Water leakages		Water delivered		Precipitation		Average age on sewer pipes		Renewed sewer pipes, average of last 3 year	
	r^2	p-value	r^2	p-value	r^2	p-value	r^2	p-value	r^2	p-value
Kambo (Ka)	0.13	0.34	0.03	0.65	0.11	0.36	0.15	0.29	0.01	0.80
Alvim (Al)	0.39	0.07	0.06	0.54	0.01	0.77	0.03	0.68	0.08	0.45
Solumstrand (So)	0.00	0.89	0.14	0.32	0.06	0.51	0.00	0.91	0.08	0.47
Sandefjord (Sf)	0.09	0.43	0.05	0.54	0.42	0.06	0.04	0.59	0.11	0.34
Knardalstrand (Kr)	0.01	0.84	0.002	0.90	0.25	0.17	0.29	0.13	0.20	0.23
Saulekilen (Sau)	0.08	0.47	0.06	0.54	0.12	0.36	0.08	0.46	0.33	0.10
Knappen (Kn)	0.34	0.10	0.28	0.14	0.04	0.63	0.00	0.96	0.28	0.14
Lillehammer (Li)	0.46	0.04	0.14	0.32	0.57	0.02	0.13	0.34	0.00	0.87
Tønsberg (Tøn)	0.44	0.05	0.53	0.03	0.06	0.53	0.22	0.20	0.08	0.46
HIAS (HI)	0.00	0.89	0.00	0.88	0.70	0.01	0.20	0.23	0.22	0.21
Nordre Follo (NoF)	0.00	0.99	0.18	0.26	0.51	0.03	0.42	0.06	0.15	0.31

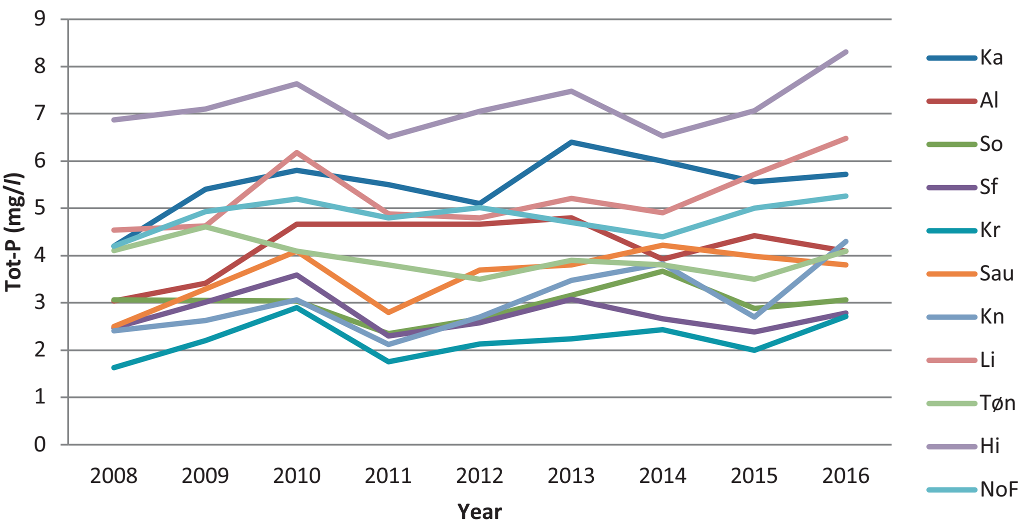

Figure 8. Development of Tot-P in the influent for different WWTP.

for HIAS and Lillehammer come as a consequence of low annual precipitation. Kambo´s low levels of I/I-water are more difficult to explain. Sandefjord and Knardalstrand both have bad results when it comes to the level of I/I-water, which cannot be explained from the results of the regression analysis.

Multivariate data analysis

As a supplement to the regression analysis, a multivariate principal component analysis was performed. The goal is to get a clearer picture of which variables influence the level of I/I-water the most in different locations. The analyses have been performed both with and without the variable "system solution" (share of combined systems).

The samples presented in the figures in this chapter are represented with an abbreviation of the name (also shown in table 5) along with the year of the sample. For instance, *Kn15* represent the value of Knappen in 2015.

PCA without the variable *system solution (share of combined system)*

The influence plot from this PCA is shown in figure 9.

The x-axis in the figure indicates how far from the centre of the model the samples are. The y-axis signifies how far from the principal component the samples are. Possible outliers are placed in the upper right corner of the plot (Camo Software AS, 2014).

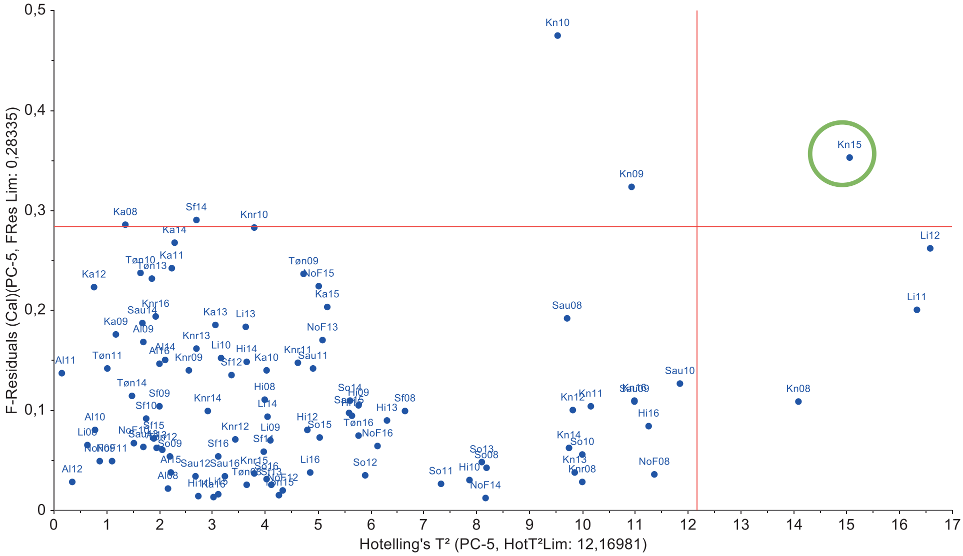

Figure 9. Influence plot of the PCA including all samples and without "system solution".

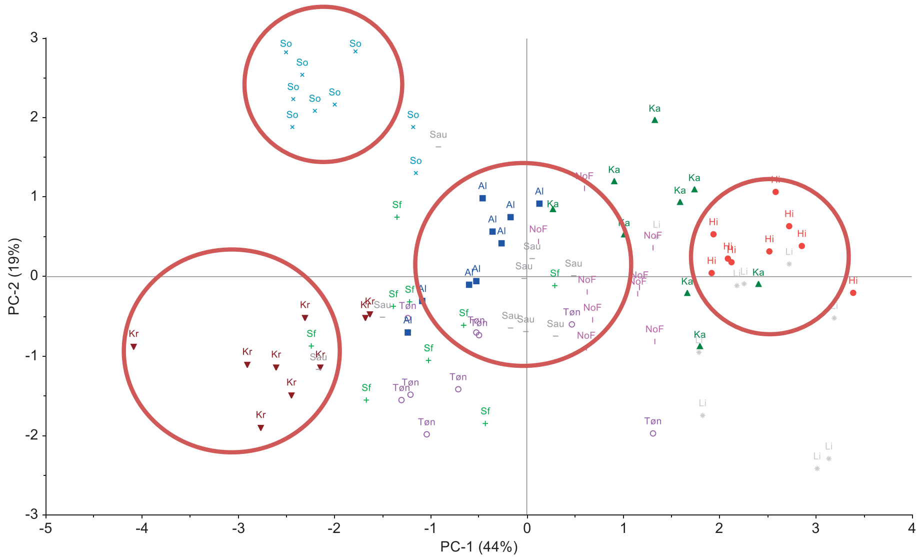

Figure 10. Scores plot of the PCA including the variable "system" and without the sample "Knappen".

The influence plot shows that KN15, which is marked out by a green circle in figure 9, may be an outlier candidate. Because of this a second model was established. The second model does not include Knappen, but includes the variable «system solution» (share of combined system).

PCA without Knappen (Kn) and including *system solution (share of combined system)*

The scores plot for this model is shown in figure 10.

PC1 and PC2 together explain about 63% (44%+19%) of the observations. The samples used in this analysis show that Solumstrand (So) and Knardalstrand (Kr) are in one end of the plot, along PC1, and HIAS/Kambo (Hi/Ka) and partly Lillehammer (Li) are in the other end of the plot. Groups on each side of the center may have opposing characteristics. PC1 is the most important PC for the spreading of the group. Other locations clustering in a group, such as Nordre Follo (NoF), Saulekilen (Sau) and Alvim (Al), have properties similar to one another.

The correlation between the loadings is shown in figure 11.

The correlation loadings plot shows that all of the investigated loadings are negatively correlated to the loading Tot-P. Variables with more than 50% variance explained are treated as significant which is the case for all of the investigated variables except for the variable *renewed*.

A high average pipe age, high amounts of delivered drinking water/leakages from the drinking water pipes, high precipitation and a high share of combined system will all lead to low values of Tot-P. All this follows an intuitive understanding of how a wastewater system is functioning.

The Scores plot and the Correlation plot may be interpreted together by placing the plots on top of each other as shown in figure 12.

It is likely that the high percentage of combined system together with a high amount of leakages from the drinking water system is the cause of Solumstrands low values on Tot-P, which is not the case for Sandefjord, Knardalstrand or Tønsberg. In these three locations the high amount of annual precipitation is most likely a key driver of the high levels of I/I-water.

The results from the PCA including the variable "share of combined system" are summarized in figure 13 and shows how the variables may be rated for each location when the locations are compared to each other.

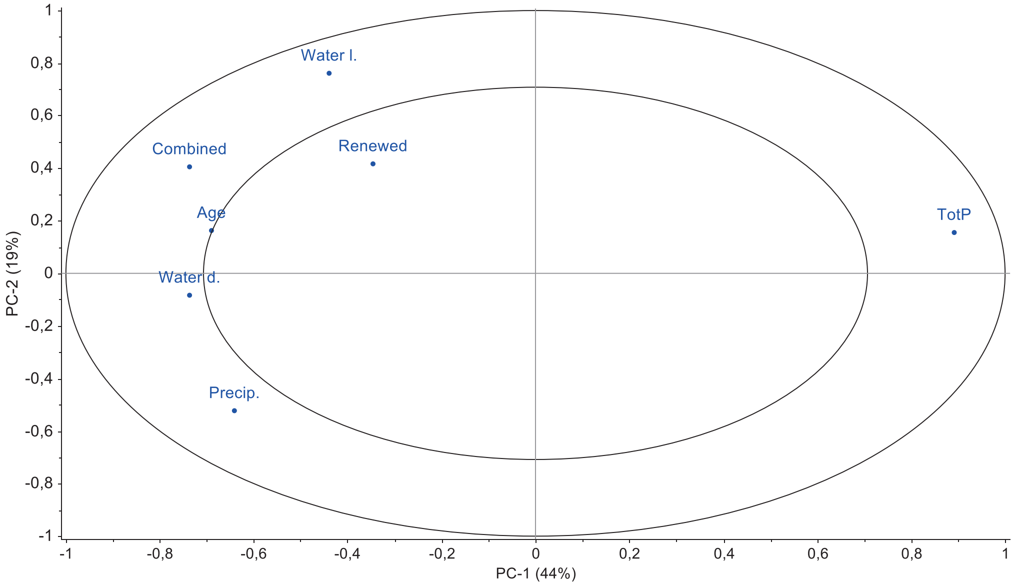

Figure 11. Correlation loadings plot for PCA including the variable "system" and without the sample "Knappen".

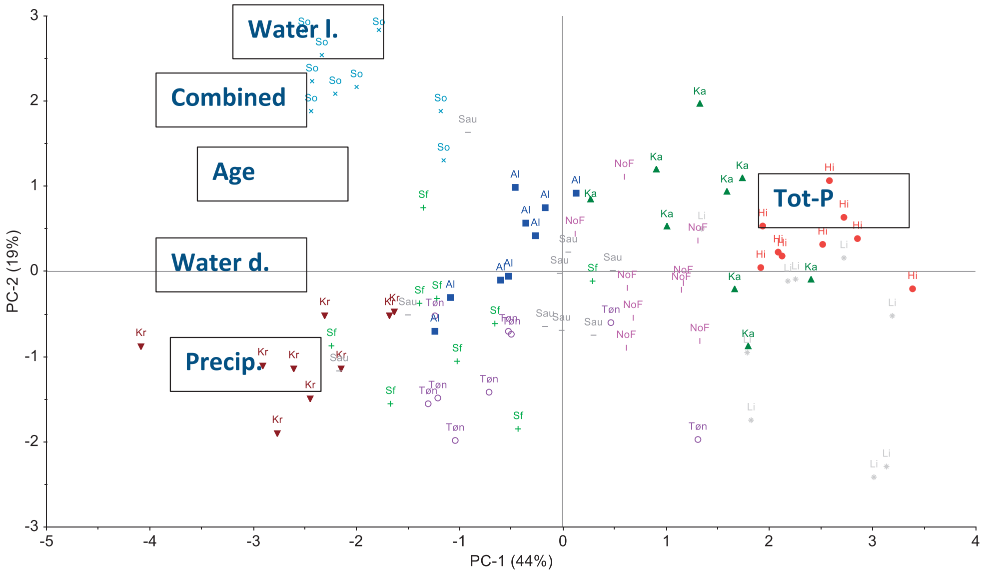

Figure 12. Interpretation of the correlation plot and the scores plot in relation to each other.

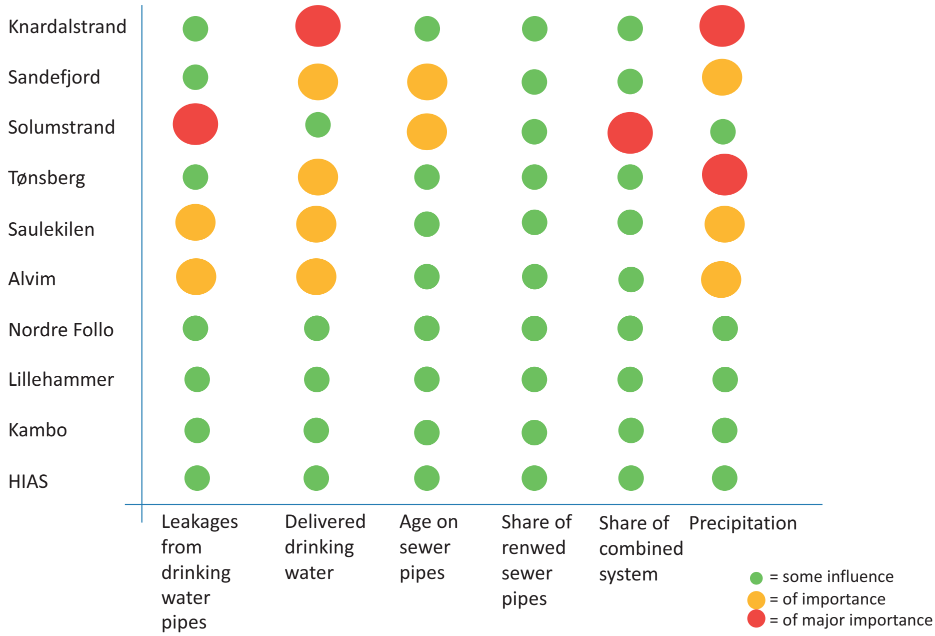

Figure 13. The results from the PCA. Each variable has been rated according to importance for each location.

Discussion and conclusions

An even more complete model including for instance groundwater levels could give more reliable results. It is essential when performing analysis to control the most important parameters. Which parameters are the most important is difficult to predict, but a multivariate data analysis might give insight into which variables are significant. However, this study shows that there are probably several influencing variables on I/I-water.

The County Governor of Oslo and Akershus encourages the municipalities in his jurisdiction to work towards an I/I-level on 30%. This may be achievable for some municipalities, especially areas with low amounts of annual precipitation. For other municipalities, this goal may be hard to reach, partly because of local factors such as precipitation patterns.

When drinking water pipes and wastewater pipes are placed in the same trench, leakages from drinking water pipes may potentially be an important source of I/I-water.

For most of the locations included in the study, all the investigated variables contribute to the complete picture of how the sewer network is affected by I/I-water. A statistical tool, like multivariate analysis, can be applied to investigate the relationships between different variables. Such a tool will help our understanding of potential hidden patterns in the datasets.

In the examples presented in this study, different municipalities have been compared to each other. By comparing different locations within the same municipality, it seems suitable to use a multivariate analysis as one of several tools when aiming to identify the most socio-economically beneficial approach to reduce I/I-water within each area. By including other variables in addition to the ones used here, for instance the share of impermeable surfaces, groundwater level and crossings between sewer pipes and rivers, a multivariate analysis may be a very useful tool to gain further insights into the driving factors of I/I-water.

Acknowledgments

The authors want to thank Asker municipality for sharing information and for giving access to data. In addition the authors want to thank the Norwegian environment agency for granting access to WWTP data. The authors also want thank Asker municipality and the Research Council of Norway for financing this study.

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Vol 82 | Issue 7 | October 2020
IWA PUBLISHING
Water Science & Technology
ISSN 0273-1223
iwaponline.com/wst

Analysing consequences of infiltration and inflow water (I/I-water) using cost-benefit analyses

Kristin Jenssen Sola, Jarle T. Bjerkholt, Oddvar G. Lindholm and Harsha Ratnaweera

ABSTRACT

The Municipality of Asker (Norway) is at risk of not meeting the water quality targets set by the European Union Water Framework Directive within the stipulated timeframe. While there are multiple factors negatively impacting water quality in the municipality, wastewater is likely to be a major contributor. Infiltration and inflow water (I/I-water) leads to a number of unwanted consequences, of which direct discharge of untreated wastewater through overflow points is particularly important. In Aker municipality the portion of I/I-water is about 63%, while the goal is to achieve a level of about 30%. This study utilises a socio-economic cost-effectiveness analysis of measures to prevent sewer overflows into waterbodies. The most effective alternative identified in the analysis is a complete renovation of old pipes in combination with troubleshooting for faulty stormwater connections, when compared to alternatives considering upsizing/retention. I/I-water cost the municipality of Asker NOK34 million in 2017, when using a price of NOK16,434 for each kg of total phosphorus (Tot-P) let into the recipient water bodies. If the phosphorus cost is equal to or less than NOK17,806/kg Tot-P, then it will not be socio-economically justified to reduce I/I-water.

Key words | cost-benefit, I-I-water, sewer, wastewater

Kristin Jenssen Sola (corresponding author)
Jarle T. Bjerkholt
Oddvar G. Lindholm
Harsha Ratnaweera
Department of Mathematical Sciences and Technology,
Norwegian University of Life Sciences,
1430 Ås,
Norway
E-mail: *Kristin.jenssen.sola@asker.kommune.no*

Kristin Jenssen Sola
The Municipality of Asker,
1372 Asker,
Norway

Jarle T. Bjerkholt
The Faculty of Technology, Natural Sciences and Maritime Sciences,
The University of South-Eastern Norway,
3901 Porsgrunn,
Norway

HIGHLIGHTS

- The article identifies three different measures against consequences of I/I-water and does an analysis of what measure provides the best cost/benefit ratio.
- In addition we have done a calculation of what the I/I- water cost the municiplity of Asker in 2017.
- In the article we provide a literature study of previous studies considering the willingness to pay to achive better water quality in the recipient waterbodies.

INTRODUCTION

Urban sewer systems

A traditional sewer system consists of both public and private pipelines as well as pumping stations, wastewater treatment plants and overflows. In overflow points (combined sewer overflow (CSO), sanitary system overflow (SSO)), wastewater can be released into water recipients such as rivers, the sea or groundwater. These overflows become operational if the sewer system is overloaded, commonly due to heavy rainfall. Non-sewage water (rainwater, groundwater and drinking water) that leaks into the sewer system is in sanitary sewer systems defined as infiltration and inflow water (I/I-water). A sanitary sewer system, henceforth referred to as a 'separate system', is not dimensioned to handle I/I-water. Ideally there should be

doi: 10.2166/wst.2020.395

no I/I-water in a separate system as stormwater would be transported in a separate stormwater drainage system. Meanwhile, a combined sewer system is dimensioned to handle the influx of certain quantities of I/I-water. In most Norwegian municipalities we find both combined sewer systems and separate sewer systems.

I/I-water may have significant economic and environmental impacts. The economic aspect relates to increased maintenance costs at pumping stations and wastewater treatment plants (WWTPs) as well as compensation payments due to basement flooding caused by insufficient capacity in the wastewater system. The environmental impact relates to discharge of wastewater to recipients through CSOs/SSOs as well as increased discharge from the WWTPs. I/I-water finds its way into the wastewater pipeline system through leaking or cracked pipes and manholes as well as incorrectly connected stormwater drains. In many wastewater systems, the volume of I/I-water depends on the amount of rainfall. Increased rainfall intensity and volumes as a consequence of climate change may therefore contribute to more I/I-water (Sola *et al.* 2018). The groundwater level is of great importance to the level of I/I-water (Karpf & Krebs 2011). Even so, this factor is only rarely measured in Norway (Sola *et al.* 2019). In a typical Norwegian trench, the stormwater pipe is situated at the bottom, below the drinking water pipe and below the sewer pipe. Therefore the storwater pipe is underneath the sewer pipe. It is, therefore, reasonable to assume that a large proportion of the I/I-water in Norwegian wastewater systems originates from incorrectly routed stormwater, leakages from drinking water pipes or from infiltrated rainwater and not so much from groundwater (Sola *et al.* 2019).

Measures, such as renovating municipal and private pipes and troubleshooting for incorrectly connected stormwater drains, will help reduce infiltration and inflow to the sewer system. Upsizing various components in the wastewater system and establishing retention basins may potentially prevent CSO/SSO but will not prevent I/I-water from entering the system and thus targets the symptoms rather than the causes of I/I-water.

Wastewater and the marine environment

Managing wastewater systems also means managing water resources. 'Lost' wastewater may have negative impacts on recipient waterbodies. The wastewater industry is governed by EU directives and Norwegian law. Of particular importance is the EU Water Framework Directive (the Water Directive, WFD), which has been incorporated into Norwegian legislation through the Water Regulation (Vannforskriften). The purpose of the Water Regulation is to 'ensure protection and sustainable use of the marine environment, and if necessary, implement preventive or enhancing environmental measures to safeguard the state of the environment…' (Vannportalen 2018). Among other things, working within the framework of the WFD entails carrying out status surveys on the water quality and developing water resource management plans. The WFD and Norwegian Water Regulation are therefore essential to take into account when setting priorities for the Norwegian wastewater industry.

International work on ecosystem services in Norway has been followed up by the Norwegian Official Report 213:10 '*Nature's Benefits – on the Value of Ecosystem Services*' (Magnussen 2016). The concept of ecosystem services highlights both the monetary and non-tangible value of the resources an ecosystem provides for human welfare. Ecosystem services thus include both physical goods and services as well as usable and non-usable values (Magnussen 2016). As such, ecosystem services are attempts to attach societal benefit values to all the services provided by an ecosystem. In many ecosystem services the marine environment plays a key role. For instance, one ecosystem service is 'recreation, mental and physical health'. This service may be linked to two environmental targets previously used for freshwater bodies in Norway, namely bathing water quality and recreational fishing (Andersen *et al.* 1997).

Socio-economic cost-benefit analyses

Socio-economic analyses entails assessing costs and beneficial effects related to possible actions, such as – in this case – abatement measures to reduce the consequences of I/I-water. The purpose is to calculate the socio-economic profitability of different measures in order to rank and compare the assessed measures (Direktoratet for økonomistyring (The Norwegian Government Agency for Financial Management) 2018). Under the term 'socio-economic analyses' we find a range of tools that may be utilised when making decisions in the public sector: cost-benefit analyses, cost-efficiency analyses and cost-effectiveness analyses (Direktoratet for økonomistyring (The Norwegian Government Agency for Financial Management) 2018). Such socio-economic analyses are based on the premise that the benefit received from a measure is likely to correspond to the willingness to pay (WTP) in the population impacted by a given policy. The benefit to households in receiving an increase in quantity or quality of an environmental good may therefore be measured as WTP (Navrud 2016).

Environmental goods are public goods which by definition are non-exclusionary and non-rivalrous. This means that if a good is available, it is available to everyone and use by one individual does not prevent the use by another (Navrud 2016). Since environmental goods cannot be distributed through markets, market rates, which would indicate their value, do not exist (Hagen & Volden 2016). Accordingly, in socio-economic analyses, the economic consequences we reap from environmental interventions are not priced directly in the market. Instead the economic consequences can either be quantified and given a monetary value or their value can be calculated without market pricing (Hagen & Volden 2016). In cases where there are no markets or reliable studies on the WTP, the valuation of marginal, external costs associated with pollution emissions may be determined by the *damage cost method*, *costs of mitigation measures* or the *abatement cost method* (Ibenholt *et al.* 2015).

The aim of the presented study is to reflect on the impacts of I/I-water in wastewater systems, and how the consequences of I/I-water may be limited. The study looks into how the costs associated with phosphorus emissions and potential mitigation measures can be quantified in order to guide decision-making in mitigation efforts. A cost-efficiency analysis has been performed, evaluating the costs and benefits associated with different measures that aim to limit the negative consequences of I/I-water and thereby prevent phosphorus discharge into waterbodies. Other indicators, like bacteria, could also have been used, but the main focus in the presented study has been the nutrient phosphorus. Reduced phosphorus emissions are likely to contribute to improved water quality in recipients. The study therefore also includes an appraisal of the population's WTP for this improvement.

The presented study is based on actual figures from Asker Municipality, Norway, and 2017 was used as the year of calculation.

METHODS

Methodology

This study was conducted in three phases, where phase 1 and 2 are illustrated in Figure 1. The third phase consisted of a literature review of potential benefits gained from improving water quality in recipients.

Phase 1: Cost-efficiency analysis:

1. Identify potential measures to reduce consequences of I/I-water
2. Calculate investment costs of measures identified in step 1
3. Calculate phosphorus emissions for all alternatives, including the baseline scenario (alternative 0)

Phase 2: Put a price-tag on I/I-water:

4. Quantify wastewater emissions due to I/I-water
5. Quantify operating costs (e.g. pumping costs) due to I/I-water
6. Calculate the cost of emissions caused by I/I-water and the total cost related to I/I-water

The third and final phase examined the benefit value of the measures identified in phase 1. The benefit value of the measures assessed in this study relate to water quality improvements. The value of improvements in water quality is examined through studies of WTP. However, we have not carried out a WTP study for the purpose of this paper, but instead relied on previous studies from which it is possible to transfer values. Value transfer entails transferring both the benefit and disadvantages values between different studies.

Changes in producers' surpluses and authorities' surpluses are not considered to be relevant to this study. As previously discussed, water quality improvements may have positive impacts on several ecosystem services where water plays a crucial role. Good bathing water quality, water suited for recreational fishing and water which may be used for irrigation are all relevant services in this regard. All of these services are valued through WTP. Reduced risk of basement flooding due to I/I-water is also included in the study. Phosphorus is a non-renewable resource, and an important component in fertilisers. By recovering phosphorus from wastewater and limiting discharges one could potentially save money. In 2015, the price of one kilogram of phosphorus in mineral fertiliser was about NOK25 (Grønlund *et al.* 2015). The sales price of phosphorus in Norway is low, and therefore this factor is not included in the calculations.

With regard to basement flooding, the current compensation costs have been used as an expense in alternative 0, while WTP to prevent basement flooding is used as a benefit value in alternatives A, B and C. When calculating benefit values for water recipients in Asker, it was assumed that all the inhabitants of the municipality would benefit from the measures considered in all alternatives.

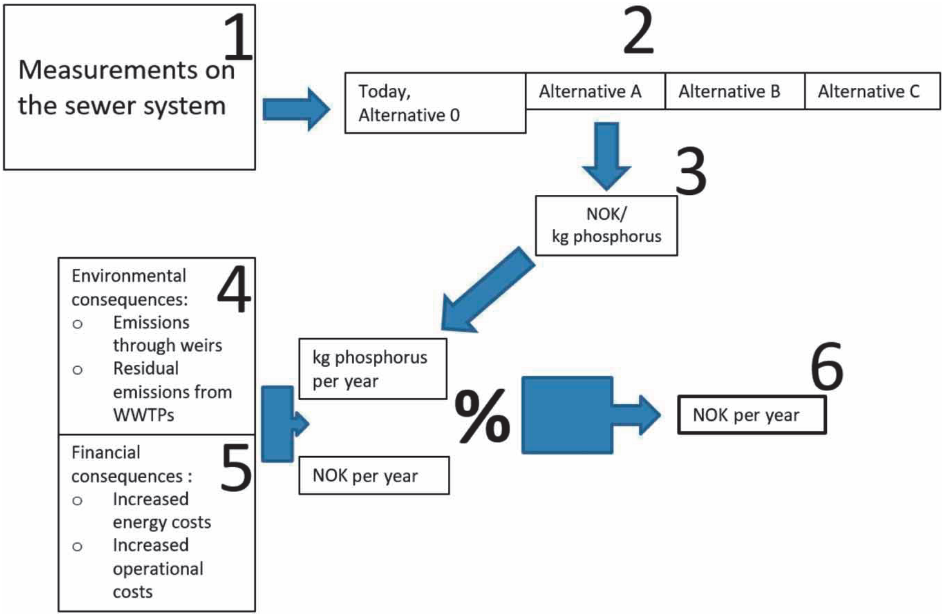

Figure 1 | Flowchart illustrating the method used to quantify the consequences of I/I-water.

Identification of pipe quality

In order to identify which pipes to renovate, several methods can be used. CCTV (closed circuit television) and distributed temperature sensing are both methods that can be used in order to locate defects. In Asker, there is extensive use of CCTV, and the municipality aims to inspect all sewer pipes. The reports generated from the CCTV inspections form the basis for selecting which pipes to renovate.

Hydraulic calculations

Due to large amounts of I/I-water, the sewer system in Asker functions as a combined sewer system, even if it is designed and operated as a separate sewer system. Figures on water volumes and capacities in the wastewater pipeline system were generated by performing calculations with a hydraulic model utilising the program Rosie, which uses Mouse (DHI software) as a calculation engine.

Pollution statement

The causes of poor water quality in Asker have been investigated by accounting for the chemical parameter of phosphorus. Elevated phosphorus emissions may cause eutrophication in freshwater and seawater (Universitetet i Oslo 2017). On the other hand, it is also a valuable resource, recovery of which is increasingly attempted due to its value as a fertiliser and rapidly diminishing mineral reserves. Phosphorus was previously used as an indicator of environmental health for freshwater bodies in Norway, and is therefore often used in pollutant calculations, particularly for freshwater bodies. For this reason phosphorus has been used as an indicator of emissions in this study. Other indicators, such as nitrogen and bacteria, could have been chosen instead.

The total phosphorus (Tot-P) discharge from Asker caused by a suboptimal wastewater system in 2017 was as follows (Asker kommune (Municipality of Asker) 2018):

Overflow (SSO):	209 kg Tot-P/year
Leakages from the sewer system:	844 kg Tot-P/year

The overflow volumes are calculated using a hydraulic model. The model is well calibrated in the areas where most of the weirs are situated and is for these areas considered to be reliable. Figures on leakages from the sewer system are based on historical figures from Norway, using standard values for specific years of construction of the sewer pipes. The figures on leakages from broken wastewater pipes are associated with uncertainty. Further analyses therefore only examine discharges caused by overflow, both from the municipality and the wastewater treatment plant VEAS. VEAS (Vestfjorden Avløpsselskap) has calculated the discharge of Tot-P via overflow to be 2.7 tonnes in 2017 (VEAS AS 2017). Asker's share of this amounts to 223 kg. Even though VEAS's emissions from overflows do not flow into Asker Municipality, Asker's share of these discharges is included in the calculations performed in the presented article. In addition, treated wastewater from the WWTP carries phosphorus into water recipients. Treated wastewater from VEAS amounted to 22.1 tonnes of Tot-P in 2017 (VEAS AS 2017). Asker's share of this was 1,828 kg Tot-P. In 2017 the total amount of emissions caused by I/I-water sums up to 1,584 kg Tot-P.

Study area

The cost-efficiency analysis performed in this study is restricted to the sewer system in Asker Municipality. Asker is located in southeast Norway, just to the southwest of Oslo, the Norwegian capital. Asker Municipality, which as of the end of 2017 had about 60,000 inhabitants, was Norway's 11th-largest municipality at the time. A map of Norway and Asker, and the sewer pipes in Asker, is shown in Figure 2.

Asker Municipality owns 70 wastewater pumping stations, about 330 km sewer pipes and about 75 km stormwater pipes. Most of the pipe system was built in the 1960s and 1970s. There are stormwater pipes in some areas, but not all. Stormwater management is based on both piping and sustainable urban drainage systems. The system also consists of about 100 weirs.

The entire wastewater pipeline system in Asker consists of a separate system. In a well-functioning separate system, there should be no exfiltration of wastewater or I/I-water. A study carried out in 2018 found that the proportion of I/I-water in the wastewater system in Asker was 63% in 2016 (Sola *et al.* 2018). The method used to calculate the share of I/I-water was the water balance method (Sola *et al.* 2018). Due to high amount of I/I-water the sewer system in Asker is functioning more like a combined wastewater system than a separate system.

The wastewater system in Asker routes wastewater through a central tunnel to the WWTP VEAS. VEAS is located in Slemmestad in Asker and receives wastewater from parts of Oslo as well as all of Asker and its northern neighbouring municipality Bærum. Asker's share of the wastewater treated at VEAS amounted to 8.27% in 2017 (VEAS AS 2017). VEAS has a CSO located at Lysaker in Bærum, which discharges into the recipient 'Indre Oslofjord'.

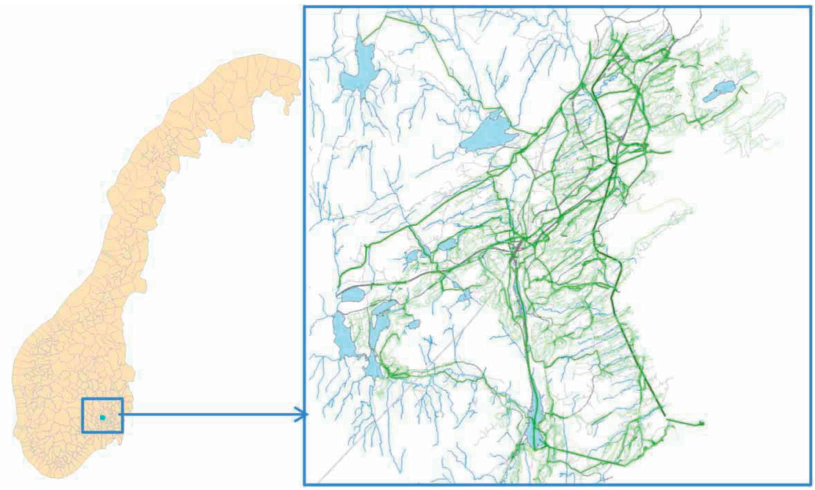

Figure 2 | Map of Norway and sewer pipes in Asker (Geodata 2018).

The County Governors in Norway may guide the municipalities regarding the level of I/I-water, and even impose measures when the level of I/I-water is too high. In 2012 the County Governor of 'Oslo and Akershus' urged the municipalities to take action against I/I-water if the level exceeded 30% as an average over the year (Fylkesmannen i Oslo og Akershus 2011). In order to combat this I/I-water it is necessary to renovate pipes, but to achieve the goal of 30% I/I-water set by the County Governor, a combination of different measures probably is necessary. The reduction in Asker has to be about 50% in order to achieve the goal.

Surveys indicate that the water quality in the Inner Oslo Fjord may be deteriorating (Lundsør *et al*. 2018). The water quality in Asker has been monitored since the year 2000, with a particular focus on chemical parameters. The development in water quality has been poor in some areas, and as of the end of 2017, Asker is not on track to meet the obligations of the WFD with regard to the biological and chemical quality of its waterbodies.

RESULTS OF THE COST-EFFICIENCY ANALYSES

Identification of different alternatives

Through the cost-efficiency analyses presented in this study, we aim to identify potential measures to reduce emissions of phosphorus caused by I/I-water.

The presented alternatives are differentiated by varying investment costs and operating costs, but they all aim at reducing the phosphorus discharge by 50%.

Alternative 0 is equal to the present situation and entails transport of pollution from the wastewater system to water recipients. In the event that no action is taken, it is likely that phosphorus discharges will increase. This increase will be driven by continuing deterioration of the wastewater system and increased frequency of sewer overflow events due to increased rainfall and volumes of I/I-water (Sola *et al.* 2018). In alternative 0, the municipality renovates a recommended minimum of pipelines, specifically 1% of the wastewater pipes per year (Norsk Vann 2015). Asker Municipality owns 70 wastewater pumping stations. Alternative 0 entails a simple upgrading of all the pumping stations over the entire 40-year period. Renovation of pumping stations is an ongoing effort similar to renovating wastewater pipes and troubleshooting for faulty connections. The costs of compensations associated with basement flooding are included in the calculations. The costs for operating municipal wastewater pumping stations and operating costs for VEAS are also included in the calculations.

Alternative A entails a complete restoration of all pipes assumed to be in poor conditions. This amounts to 65 km of pipelines, which corresponds to approximately 20% of the wastewater pipes in Asker. These pipes are being restored over a 5-year period. This is ambitious but achievable. In Asker the normal renovation rate is about 2% per year. Alternative A entails a minimum cost for renovating all the pumping stations. Alternative A is expected to reduce infiltration. In theory, this alternative would eliminate overflow both from the municipal wastewater system and from the VEAS WWTP. For this to happen, incorrectly routed stormwater must also be eliminated. This is not possible with restoration only and fieldwork is required to identify cross-connections between the stormwater network and the wastewater network. Such fieldwork is included in Alternative A. The fieldwork includes two persons working 2 days a week trying to locate and remove faulty stormwater connections. Therefore, it is assumed that this alternative will halve the volume of I/I-water.

An assumption in the calculations is that the share of I/I-water for 2017 is the same as in 2016, i.e. 63%. We further assume that if half of the I/I-water is eliminated, the reduction in discharge through overflow will correspond to the reduction in I/I-water, i.e. 32%. It is also assumed that 32% of Asker's share of I/I-water entering the VEAS facility is eliminated. This measure will accordingly reduce the Asker share of residual discharge from VEAS by 32%. The measure is assumed to eliminate the risk of basement flooding caused by I/I-water. Operating costs for the municipality will be reduced by 32%. For VEAS the operating cost will be reduced somewhere between 0 and 32%. The operating cost for VEAS will vary by 1% when using a reduction between 0 and 32%. This variable is of minimal importance to the total costs. In the calculation it is assumed that the reduction will be 20% for VEAS.

Alternative B entails increasing the pump capacity of all undersized pumping stations as well as upsizing the pipes connected to these stations that lack sufficient capacity. In total, this alternative covers 33 municipal pumping stations and approximately 3,600 metres of pumping pipes. In addition, 10 local overflow points and a total of 2,000 metres of pipes connected to local SSOs will be upsized. Furthermore, a retention basin will be built at VEAS to prevent overflow-related discharge. These upsizing projects and the establishment of a retention basin will be carried out over the course of a 5-year period. This measure comes with a minimum cost for renovating the remaining pumping stations as well as renovating 1% of the pipes per year.

Alternative B will eliminate local discharge from overflow events and as a consequence transport increased amounts of wastewater to VEAS. Since a retention basin will be built at VEAS, the overflow discharge there will also be eliminated. The basin at VEAS will be dimensioned to handle the additional quantities of water pumped into VEAS as well as Asker's share of overflow at VEAS. Alternative B will eliminate the risk of basement flooding due to poor capacity in the wastewater pipeline system. Operating costs for the municipality and VEAS will increase.

In **alternative C**, local retention basins will be established in different locations around the municipality as well as at VEAS. The basins will be connected to the SSOs that are most prone to overflow. For the sake of simplicity, the costs have been calculated for a single, representative basin. This measure will not affect exfiltration from wastewater pipes or residual discharge from VEAS. A basin will also be established at VEAS to handle Asker's share of overflow discharge there. The retention basins will be established over 5 years. This measure also comes with a minimum cost for renovating the remaining pumping stations as well as renovating 1% of the pipes per year.

Investment costs

The annuity method is used to calculate the annual cost an investment will have over the course of the period which the system is assessed to run for. The present value of the system is distributed over the entire lifespan of the system. Pipes installed today are expected to have a 100-year lifespan. Pumping stations are generally assumed to have a 50-year lifespan. Nevertheless, the lifespan of all the components in a wastewater system is set to 40 years (Det kongelige finansdepartement (The minestry of Finance) 2014). In all projects where future impacts need to be assessed, a discount rate should be applied. By using a discount rate, future benefit values and costs are assigned a lower value in the analysis than the present-day value would be. The discount rate for public sector initiatives is determined by the Norwegian Ministry of Finance and has been set to 4% (Det kongelige finansdepartement (The minestry of Finance) 2014).

Costs relating to pipe restorations

Alternative 0: The average price to restore one metre of pipe has been set on the basis of experiences through different projects carried out in Asker. For no-dig renovation projects, the price per metre has been set to NOK10,000, and for full re-digging, the price has been set to NOK23,000 per metre. We assume that the recommended renovation rate of 1% a year is sufficient, and that these pipes will be renovated in the simplest and cheapest way.

Alternative A: The number of pipes that require upgrading has been retrieved from the municipality's database, Gemini VA. Sixty-five kilometres of pipelines are assumed to be in poor condition. These are mainly concrete pipes installed before 1970. Further, it is assumed that half of these pipes can be restored in the easiest and simplest way while the other half must be dug up and replaced with new pipes.

Alternative B: In alternative B, a cost has been included for renovating pipes similarly to alternative 0, starting from year 6. Included in this calculation are all the pipelines that will not be upsized.

Alternative C: In alternative C the cost for renovating pipes is equal to alternative B.

Costs associated with upsizing of pipes and pumping stations

Upsizing of undersized pipes will cost around NOK23,000/metre, and it is estimated that there are 5,600 metres of pipes that require upsizing (2,000 metres of gravity pipes and 3,600 metres of pumping pipes). The cost of upsizing 33 pumping stations has been calculated to a total amount of NOK250 million.

Costs of establishing a retention basin at VEAS

In 2017, a project was carried out to assess the possibility of establishing a new wastewater tunnel in Asker. The purpose of the tunnel would be to retain water from some of the largest CSOs in the municipality. The cost of this tunnel was estimated to be NOK119 million for 60,000 m^3 (Serch-Hanssen *et al.* 2017). Calculations based on the 10-year rainfall projection show that approximately 33,000 m^3 of water overflows from the municipality's SSOs. A review of annual reports from VEAS shows that Asker's share of the overflow discharge from the wastewater treatment plant averaged 130,000 m^3 annually during the period of 2009–2018 (VEAS AS 2018). In total, the retention basin has to be dimensioned for 163,000 m^3, and the estimated cost is NOK323 million. This applies to alternative B.

Cost of establishing local retention basins

In alternative C, a local retention basin will be established at an estimated cost of NOK65 million. An additional retention basin will be established at VEAS to handle Asker's share of overflow discharge for a cost of NOK258 million.

Operating costs

I/I-water amounted to 63% of all wastewater in Asker in 2016 (Sola *et al.* 2018). The additional operating costs due to I/I-water for the municipality are mainly driven by extra pumping. Calculations performed by Asker Municipality show that, in 2017, the municipality's wastewater pumping stations required 5,050,867 kWh (Sommerro 2018). Given a price of NOK1.12/kWh, this corresponded to a price of approximately NOK5.66 million. Operating costs at VEAS in 2017 amounted to NOK324 million. Of this, 'maintenance' made up NOK73 million of the costs and 'electrical power' made up approximately NOK15 million (VEAS AS 2017). Other costs associated with operation of the plant are unlikely to be significantly impacted by reductions in I/I-water and are therefore not taken into account (Johansen 2019). Both maintenance and electrical power are assumed to be reduced by 20% when reducing the amount of I/I-water.

Operating costs, municipal

Alternative 0: Operating costs due to I/I-water amounted to NOK5.66 million in 2017, which corresponds to municipal operating costs in alternative 0. Over the entire 40-year period, the operation of pumping stations will cost approximately NOK113 million in alternative 0.

Alternative A: If the volume of I/I-water is halved, the amount of wastewater pumped will be reduced by 32%. The maximum reduction in pumped wastewater will be achieved when all the measures in this alternative have been fully implemented. The construction period is set to 5 years. The calculated operating costs per year from (and including) 2024 amounts to NOK3.85 million. From the years 2019 up to and including 2023, the operating costs will gradually decline on an annual basis. The operating cost of the municipal pumping stations is estimated to be approximately NOK81 million for the entire period. This alternative also includes cost due to increased fieldwork. We assume that two people work twice a week troubleshooting for faulty stormwater connections, following up on house owners etc.

Alternative B: If we opt for upsizing the system rather than renovating, the costs related to pumping operation will increase. If we assume that upsizing will result in a 50% increase in operating costs, then this amounts to NOK8.49 million per year. There will be a gradual rise in pumping costs from the year 2019 up to the year 2024. In total, these costs will amount to NOK164 million.

Alternative C: This alternative will result in increased pumping costs. Because the water is retained locally, each station connected to a basin will have to pump more than in alternative 0. In addition, a basin will become an additional operating point for the municipality. An additional cost is added for operations for alternative C.

Operating costs, WWTP-VEAS

Alternative 0: Asker's share of I/I-water costs at VEAS amounted to approximately NOK7 million in 2017, which corresponds to alternative 0.

Alternative A: It is uncertain how much of a reduction in costs can be expected if the I/I-water into the plant will be halved, but in the following a reduction of 20% is assumed. Therefore, in alternative A, the operating costs for VEAS fall to NOK5.6 million after the year 2024.

Alternatives B and C: In alternatives B and C, we assume that the operating costs will increase by 50%, meaning a gradual increase to NOK10.5 million per year after the year 2024.

In Table 1 the results of the cost calculations are shown.

The analyses shows that alternative A, including a full renovation of all bad sewer pipes and increased efforts to remove faulty stormwater, will be the cheapest measure. There is only NOK68 million between alternative A and C.

It is possible that an I/I-water reduction of 50%, which was used in alternative A, is a somewhat high figure. In the event that we would have to restore an even higher percentage of the pipes in order to achieve the goal of 50% reduction in I/I-water, the total cost of all considered alternatives will be as shown in Table 2. We have investigated the costs when renovating 20, 25 and 30% of the sewer pipes.

If we have to restore more than 20% of the sewer pipes in order to reduce the level of I/I-water by 50%, alternative C will be the most profitable. If we have to restore more than 25% of the pipes in order to reduce the level of I/I-water by 50%, then also alternative B will be more profitable than alternative A.

Wastewater emissions due to I/I-water

Calculations of overflow and pollution transport

The included amounts of overflow are in the presented study caused entirely by I/I-water, but the included part

Table 1 | Results from cost calculations

	Alt. 0	Alt. A	Alt. B	Alt. C
	Present value in NOKmillions			
Financial costs				
Renovating pipelines, 1% a year	−560			
Renovating old pipelines		−955	−579	−579
Field work		−8		
Upsizing pipelines			−115	
Renovating pumping stations	−125	−125		−125
Upsizing pumping stations			−223	
Operating pumping stations	−113	−81	−164	−164
Continuously renovating, VEAS	−253	−253	−253	−253
Operating costs, VEAS	−140	−114	−203	−198
Establishing retention basin, VEAS			−285	−231
Establishing retention basin, locally				−53
Compensations payments				
Total costs	**− 1,191**	**− 1,536**	**− 1,822**	**− 1,604**

of the residual emissions from VEAS is based on the share of I/I-water, 63%. Based on these prerequisites the current discharges for Asker Municipality associated with I/I-water sums up to 1,584 kg Tot-P in 2017. By including the measures in alternative A, B or C the emissions will be reduced. The development of I/I-related emissions of phosphorus in all alternatives is shown in Table 3.

Alternative A will be the alternative where most phosphorus is being removed.

The costs associated with removal of phosphorus in the different alternatives calculated in this study, indicated as the value in NOKper kg of removed phosphorus, sums up to:

Table 2 | Total cost for all alternatives when renovating 20, 25 or 30% of the sewer pipes in alternative A

	Alt. 0	Alt. A	Alt. B	Alt. C
	Present value in NOKmillions			
Total costs, 20% renovation in alternative A	−1,191	−1,536	−1,822	−1,604
Total costs, 25% renovation in alternative A	−1,191	−1,795	−1,822	−1,604
Total costs, 30% renovation in alternative A	−1,191	−2,030	−1,822	−1,604

Alternative A: Rehabilitation of pipelines/ troubleshooting for stormwater:	NOK79,060
Alternative B: Upsizing locally and establishing retention basins at the WWTP:	NOK110,127
Alternative C: Retention locally and at the WWTP:	NOK104,863

Alternative A is the best alternative in relation to cost-efficiency.

RESULTS OF THE COST CALCULATION OF I/I-WATER

Pricing of phosphorus discharge

Emissions of phosphorus may be priced using different methods. For example, one can identify a price per kilo of phosphorus treated in a wastewater treatment plant through indirect public valuation (Karstensen 2015). In 2017, VEAS treated 364 tonnes of Tot-P at an operating cost of NOK268

Table 3 | Discharges of phosphorus due to I/I-water in all considered alternatives

	2017, kg Tot-P	2059, kg Tot-P	2019–2059, kg Tot-P
Alternative 0	1,584	1,584	64,929
Alternative A	1,584	1,077	45,498
Alternative B	1,584	1,152	48,384
Alternative C	1,584	1,152	48,384

million. This cost also includes, for instance, removing of nitrogen and bacteria, but for the simplicity we assume that the cost is only related to removal of phosphorus. This results in a price of NOK736 per kg of treated phosphorus. One can also compute the annual cost of establishing a new wastewater treatment plant. Karstensen (2015) estimates this cost as NOK1,241/kg (Karstensen 2015). The 2017 value of NOK1,241 per kg (2015) is NOK1,337 per kg. This is the annual cost for both establishing and operating a new plant, similar to the existing WTP Bekkelaget in the municipality of Oslo. Through the 'Action Lake Mjøsa' project (1975), the goal of which was to reduce pollution in Lake Mjøsa, the authorities set an upper limit of NOK3,000/kg reduction in Tot-P for the measures they wished to fund (Karstensen 2015). This is equivalent to NOK16,434/kg in 2017 value.

Total costs due to I/I-water

The costs due to I/I-water for a specific year, when using different prices on emissions of phosphorus, are calculated according to formula (1):

$$\text{Total costs of I/I-water} = \text{operating costs due to I/I-water} + \text{emissions costs due to I/I-water} \quad (1)$$

The costs due to I/I-water for Asker in 2017 are summarised in Table 4. The figures in alternative A, B and C are based on the present value over a period of 40 years.

By using the figures that emerge from the calculations presented in this study, the cost related to I/I-water will range between NOK137 million and NOK187 million. If one uses more conservative estimates, such as the figure of NOK16,434 per kg of phosphorus from the Action Lake Mjøsa project, the cost of I/I-water in Asker Municipality will be NOK34 million for 2017.

Table 4 | Summary of costs generated from I/I-water for Asker Municipality in 2017

Source	Costs per kg phosphorus (NOK)	Costs related to I/I-water in 2017 (million NOK)
Operating the WWTP (literature)	736	9
Establishing new WWTP (literature)	1,241	10
Authorities' WTP, Action Lake Mjøsa project (literature)	16,434	34
Alternative A	79,060	138
Alternative B	110,127	187
Alternative C	104,863	178

By including emissions of phosphorus in alternative 0 and A, and by using the cost of NOK16,434/kg phosphorus, the total costs for these alternatives will amount to:

Alternative 0: NOK1,190 million + (64,929 kg Tot-P × NOK16,434/kg Tot-P) = NOK2,258 million

Alternative A: NOK1,524 million + (45,498 kg Tot-P × NOK16,434/kg Tot-P) = NOK2,272 million

Implementing measures to combat I/I-water will not be profitable in this example.

When using the value of NOK79,060 per kg of removed phosphorus, as calculated for alternative A, the total costs of the alternatives will amount to:

Alternative 0: NOK1,190 million + (64,929 kg Tot-P × NOK79,060/kg Tot-P) = NOK6,323 million

Alternative A: NOK1,516 million + (45,498 kg Tot-P × NOK79,060/kg Tot-P) = NOK5,113 million

When using the price of NOK79,060/kg Tot-P it will be profitable to implement measures according to alternative A.

We can examine the limiting value for phosphorus costs by comparing the costs for alternative 0 and alternative A, as shown in formula (2).

$$\begin{aligned} &\text{Alternative 0: present value of investments} \\ &+ \text{present value of operating costs} \\ &+ \text{emissions (kg Tot-P)} \times \text{emissions costs (NOK/kg Tot-P)} \\ &= \text{Alternative A: present value of investments} \\ &+ \text{present value of operating costs} \\ &+ \text{emissions (kg Tot-P)} \times \text{emissions costs (NOK/kg Tot-P)} \end{aligned} \quad (2)$$

$$\text{NOK 1,190 million} + (64{,}929\,\text{kg Tot-P} \times \text{NOK X/kg Tot-P}) = \text{NOK 1,536 million} + (45{,}498\,\text{kg Tot-P} \times \text{NOK X/kg Tot-P})$$

$$X = \text{NOK 17,806/kg Tot-P}$$

As such, if the phosphorus cost is equal to or less than NOK17,806/kg Tot-P, then it will not be socio-economically justified to reduce I/I-water.

RESULTS OF CALCULATIONS OF BENEFITS

Valuation of satisfactory fishing conditions. Norwegian conditions

In 2018, a study was carried out which among other things assessed the benefit value as the WTP for extermination of invasive fish species such as pike and minnow in efforts to improve conditions for indigenous fish populations in

Trøndelag, Norway. Participants in the study indicated a WTP for such a measure not only in local fishing areas, but also for the rest of the country (Magnussen *et al.* 2018). The quoted amounts represent a lump sum per household.

Pike, the whole country:	NOK1259–1,893
Pike, just own county:	NOK909–1,362
Minnow, the whole country:	NOK1,034–1,659
Minnow, just own county:	NOK737–1,185

Valuation of clean water. Norwegian studies

In 2015, an assessment of benefits and cost of environmental measures for urban waterways was published (Magnussen *et al.* 2015). The authors conclude that WTP for an improvement in water quality among people living closer than 1,000 metres from the waterways Alna (70,000 people) and Hovinbekken (30,000 people) in Oslo (Norway) amounted to NOK1,400 per person and NOK2,467 per person respectively (Magnussen *et al.* 2015). The study does not differentiate between the various benefits of an improvement in water quality. In other words, it covers everything from better bathing water to better cultural experiences.

A study from 2010 carried out 10 sample surveys in Europe, one of which was carried out in Østfold/Akershus (Barton & Holen 2010). The study was a part of the project AQUAMONEY, and focused on the recreational use of lakes, and investigated local residents' WTP for improvements in the ecological status of those environments. The study found that the WTP among the respondents ranged from NOK1,070 to NOK2,000 per household per year for the lakes Vansjø and Storefjorden. The study also showed that WTP fell by approximately NOK25/km and NOK72/km the further away from the lakes a person lived (Barton & Holen 2010).

In a study by Holen *et al.* (2011), for Sørum Municipality, it was found that the public's WTP had to amount to approximately NOK5,700 per household per year for at least 40 years for the benefit value of measures to improve the water quality in waterways within the municipality to be socio-economically justifiable (Holen *et al.* 2011).

Valuation of bathing water quality: European studies

There are several European and international studies which have examined WTP for better bathing water quality. The presented study has only used results from European studies. The figures vary from NOK86/person per year (Ireland) to NOK1,176/person per year (Denmark) (EVRI 2019). A study on WTP was carried out by Swanberg and Wallström, in Gothenburg, Sweden in 2018. The study concludes that WTP for improvements to water quality ranges between SEK50 and SEK58 per household per month (Swanberg & Wallström 2018). This corresponds to approximately NOK260–303 per person per year.

Valuation of prevented basement floodings

Basement floodings can be a great burden on those affected, both financially and psychologically. People who have experienced floodings are often anxious of it happening again. A study carried out in the Norwegian municipalities Øvre Eiker and Nedre Eiker established that the difference between the WTP between a broader insurance against flooding and physical initiatives to prevent flooding amounted to NOK92/year per household (Grann 2011). When converted from 2011 values to 2018 values, this figure is NOK112. In 2017, a study was carried out in Norway which established that uncertainty costs related to flooding can be valued at NOK400 per household per year for houses located more than 1 km from areas that have previously experienced flooding. For houses located in areas particularly vulnerable to flooding, a figure ranging from NOK800 to NOK900 per household per year was indicated (Torgersen & Navrud 2017).

In further analyses the following figures are being used to quantify basement floodings due to poor capacity in the wastewater pipeline system:

- NOK400 per house per year for houses located 1–5 km from properties which have previously experienced flooding
- NOK800 for houses located closer than 1 km from houses which have previously experienced flooding

Summary of relevant WTP studies

Table 5 provides a summary of relevant studies relating to WTP.

The benefit value of water quality improvement in this study uses the average value of NOK554 and NOK2,709, i.e. NOK1,632 per person/year. The total number of affected properties corresponds to the total number of persons living in Asker, i.e. 61,400 (Statistisk Sentrabyrå (Stastistics

Table 5 | Summary of figures used in the calculations in relation to WPT (2018)

Valuation field	Country	Lower limit (NOK)	Upper limit (NOK)
Good fishing conditions (lump sum)	Norway	734 (pike)	1,893 (minnow)
Improved water quality (person/year)	Norway	554	2,709
Improved bathing water quality (person/year)	Ireland/ Denmark	86	1,176
Improved water quality (person/year)	Sweden	260	303
Avoided basement floodings (per house)	Norway	400	800

Norway) 2018). This sums up to a total of NOK1,999 million. This monetary value is used in all the considered alternatives. All alternatives will lead to the same improvement in water quality.

COST-BENEFIT ANALYSIS

Table 6 provides a summary of the calculated values discussed in this chapter. Values for WTP for avoided basement floodings, as well as compensation payments for basement floodings, have not been included as there were no reported cases of basement floodings caused by poor capacity in the wastewater pipeline system in 2017.

If one takes the beneficial value into account, then all considered alternatives are profitable from a socio-economic perspective.

DISCUSSION

The level of I/I-water in many Norwegian municipalities is high. The reasons for this are likely to be a combination of many factors. Old pipes, large portions of leakages from drinking water and incorrectly routed stormwater are all

Table 6 | Summary of costs and benefits for all alternatives

	Alt. 0	Alt. A	Alt. B	Alt. C
	Present value in NOKmillions			
Financial benefit value				
WTP to avoid basement floodings				
WTP to achieve improved bathing water quality, low				
WTP to achieve improved bathing water quality, medium		1,999	1,999	1,999
WTP to achieve improved bathing water quality, high				
Avoided costs due to basement floodings				
Total benefit value	**0**	**1,999**	**1,999**	**1,999**
Financial costs				
Renovating pipelines, 1% a year	−560			
Renovating old pipelines		−955	−529	−529
Fieldwork		−8		
Upsizing pipelines			−115	
Renovating pumping stations	−125	−125		−125
Upsizing pumping stations			−223	
Operating pumping stations	−113	−81	−164	−164
Continuously renovating, VEAS	−253	−253	−253	−253
Operating costs, VEAS	−140	−114	−203	−198
Establishing retention basin, VEAS			−285	−231
Establishing retention basin, locally				−53
Compensations payments				
Total costs	**− 1,191**	**− 1,536**	**− 1,822**	**− 1,604**
Net benefits	**− 1,191**	**475**	**177**	**395**

variables that are likely to contribute. Renovating sewer pipes and manholes will improve the situation. It is possible that renovating drinking water pipes will be an even more cost-efficient measure due to the fact that this also will limit the amounts of lost drinking water. This should be investigated.

There is significant uncertainty associated with the amount of I/I-water that can be eliminated through renovating pipes. The amount of I/I-water that can be eliminated through pipe renovation should, therefore, be examined for each specific drainage area/municipality. There is also uncertainty associated with the amount of I/I-water that can be eliminated through fieldwork. Although numerous methods may be used when searching for I/I-water, some of these methods require quite an extensive use of fieldwork. If we would have to renovate a higher percentage than 20, as included in alternative A in the presented study, then alternative C would be the most profitable one.

A cost-benefit analysis can be a helpful tool to highlight costs and benefits that are not traditionally valued in wastewater projects. A cost-benefit analysis can contribute to a greater recognition of issues such as the non-tangible value of the marine environment and ecosystem services and, in doing so, lay the foundation for increased efforts to prevent the discharge of wastewater. Specific studies of WTP have not been carried out. The figures that have emerged regarding WTP are therefore associated with some uncertainty. The monetary value of improvement in water quality is also assumed to be the same for all considered alternatives.

The valuation of preventing basement floodings is also an important factor which ought to be included in the assessment of benefits and costs in urban wastewater projects. The costs associated with compensation payments and benefit values resulting from savings related to basement floodings were found to be negligible in this study. For other municipalities, this contribution could be significant.

The analysis carried out in this study shows that there is probably a basis for setting the target restoration rate of the wastewater pipeline system higher than 1%. Adding an extra expense to the present wastewater fees and earmarking that money to upgrading the wastewater system would increase the chances of achieving the objectives set in the EU Water Directive. The current strategy is unlikely to prevent the current system from declining while making improvements at the same time. Previously conducted studies of WTP for improvements in water quality suggest that it is possible to shift some of the costs for further efforts to improve water quality on to the inhabitants of Norway.

A risk and vulnerability assessment of the wastewater pipeline system in Asker has previously been carried out. The analysis provides an overview of the critical discharge points in the wastewater system. The analyses performed in this study could have taken into account and weighted the consequences of discharges, which would have provided a more representative picture. For example, VEAS's overflow discharges and residual discharges into deep water do not have as big an impact as local discharge points.

The figures used in the presented study are based on constructions built in Asker. The figures are considered reliable when it comes to local conditions in Asker. In other cities the conditions might be quite different. It is important to use figures retrieved from experiences with local constructions. The most reliable figures on investment costs from Asker emerge from pipe renovation. When it comes to building retention basins, both locally and at the

Table 7 | Reliability of input data

	Data reliability		
Factor	**High**	**Medium**	**Low**
Pipe quality	x		
Volumes of overflow in Asker		x	
Volumes of overflow from VEAS	x		
Share of I/I-water	x		
Reduced share of I/I-water			x
Reduced operating costs Asker	x		
Reduced operating cost VEAS		x	
Costs of upsizing pumping stations	x		
Costs of building retention basins		x	
Cost of renovating pipes	x		

WWTP, experience show that it is more likely that expenses will be higher rather than lower than what is calculated in this study. This goes in favour of alternative A.

The data reliability related to figures used in the presented study is illustrated in Table 7.

By eliminating the factors related to some uncertainty the results in the presented study would be even more reliable. The most important factor to investigate further is how large a share of I/I-water could be eliminated through renovation of pipes.

CONCLUSIONS

The presented study shows that there are a number of possible measures that could be implemented to minimize the consequences of I/I-water. We found that alternative A, which entails an increased rate of sewer pipe restoration in combination with fieldwork, provides the highest net benefit value. A cost-efficiency calculation also shows that this alternative would be the most favourable. In alternative A, it would cost NOK79,060 to remove 1 kg of phosphorus, while the most expensive alternative, which includes upsizing and retention, amounts to NOK110,127 per kg.

The presented study indicates that the cost of I/I-water in Asker Municipality amounted to NOK34 million in 2017, assuming a price on emissions of phosphorus of NOK16,434 per kg. The price of I/I-water is dependent on the price on emissions of phosphorus. When using the price of NOK79,060/kg phosphorus, calculated in alternative A, the I/I-water cost NOK138 million; however, we found that reducing I/I-water will be profitable as long as the price of phosphorus emissions exceeds NOK17,806/kg.

A review of previous studies regarding WTP for improved water quality indicates that there is probably room to increase the annual water and wastewater charges in Asker by NOK1,632 per household. On this basis all the considered alternatives would be socio-economically profitable.

ACKNOWLEDGEMENTS

The authors want to thank Asker Municipality for willingly sharing information and for giving access to data. The authors also want thank Asker Municipality and the Research Council of Norway for financing this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 26 May 2020; accepted in revised form 7 August 2020. Available online 19 August 2020

What effect does rehabilitation of wastewater pipelines have on the share of Infiltration and Inflow water (I/I-water)?

Kristin Jenssen Sola 1,2,*, Jarle Tommy Bjerkholt 1,3, Oddvar Georg Lindholm 1 and Harsha Ratnaweera 1
1 Faculty of Mathematical Sciences and Technology, Norwegian University of Life sciences, 1430 Ås, Norway; jarle.t.bjerkholt@usn.no (J.T.B.); oddvar.lindholm@nmbu.no (O.G.L.); harsha.ratnaweera@nmbu.no (H.R.)
2 The Municipality of Asker, 1372 Asker, Norway
3 Faculty of Technology, Natural Sciences and Maritime Sciences, University of South-Eastern Norway, 3603 Kongsberg, Norway

Correspondence: kristin.jenssen.sola@asker.kommune.no; Tel.: +47-41-63-21-84

Abstract

The share of infiltration and inflow water (I/I-water) is predominantly driven by rainfall. This makes it difficult to document the efficiency of mitigating measures. One way to address this issue is to compare data from rehabilitation areas to areas where no measures have been implemented. Three rehabilitation areas were assessed applying this approach. The assessment shows that the rehabilitation of municipal pipes have reduced the share of I/I-water only limited. In separate systems other measures than renovations of pipes should be considered when aiming to reduce I/I-water.

Index Terms

Infiltration and Inflow water (I/I-water), measures, measurements, overflow, wastewater.

1. Introduction

Most of the Norwegian water and wastewater utilities participate in a yearly benchmarking system. The benchmarking of 2019 states that the development of the water and wastewater services is not satisfactory at a national level and poses by this an increased effort to improve the situation [1].

A number of indicators may be used in order to assess the state of the water and wastewater systems. Indicators commonly used are volumes and frequency of overflows, amount of infiltration and inflow water, the number of basement floodings and renovation rate [1, 2]. These indicators may be divided into two main categories: indicators aiming at measuring the functionality of the system and indicators aiming at measuring the condition of the system. Infiltration and inflow water (I/I-water) reflects wastewater system malfunctions and may therefore be used as an indicator on the functionality of wastewater systems.

Wastewater systems are composed by components as manholes, pipes and pumping stations that all are affected by multiple pressures such as ageing and deterioration, climate changes with an increased amount of rainfall and urbanization [3, 4]. I/I-water stems from groundwater, rainfall, rivers and drinking water leakages [2, 5-8]. The sources that contribute the most to the share of I/I-water vary geographically. However, in most places, annual rainfall strongly influences the share of I/I-water in the wastewater pipeline system [5, 9, 10]. This means that climate changes most likely will contribute to larger amounts of I/I-water. This also means that in two otherwise identical localities, the area with higher annual rainfall is likely to have higher rates of I/I-water. In other words, a- year-to year-comparison of quantities of I/I-water within the same area is of limited value.

Excessive I/I-water has both social, economic and environmental impact. The economic consequences are associated with increased pump operation and less efficient treatment at wastewater treatment plants (WTP). The environmental consequences are linked to overflow discharge, increased outflow of pollutants due to increased flow of water through the WTP and lower treatment rates at the WTPs [2, 8, 11, 12]. The social aspects are linked to the number of basement floodings and potentially reduced access to clean water [11].

A simple method to determine the share of I/I-water in wastewater systems is to measure the flow in the wastewater pipeline system, and compare this measured flow to the number of person equivalents (PE) connected and drinking water use in that same system [2, 9]. This method is called the water balance method. Another commonly used method in Norway to calculate the level of I/I-water is the dilution method [9, 13, 14]. Input to this method are measurements of for instance total phosphorus (TOT-P) into the wastewater treatment plant (WTP), the number of connected PE, and assumptions on total phosphorus production per person per day [9, 13]. Both methods have drawbacks. The water balance method does not include water that disappears out of the system through overflow points. The water balance method depends on measured figures on drinking water consumption, the dilution method depends on figures related to TOT-P production/pe/day. In both methods, there are uncertainties related to measuring equipment/measuring methods.

Renovating sewer pipes, establishing retention basins and upsizing of undersized components (bottlenecks) in the wastewater system are all traditional ways of dealing with unwanted impacts from I/I-water on the wastewater system [11]. Rehabilitating wastewater pipes results in improving both the condition and the functionality of the pipes. To identify which pipes to renovate, a Closed Circuit TV inspection (CCTV) may be used [8]. As the amounts of I/I-water are largely influenced by rainfall, water flow measurements, carried out before and after measures have been implemented, are unlikely to be comparable. Rainfall varies greatly, both in terms of geography and time, and it is challenging to identify two completely identical precipitation events. One workaround would be to compare I/I-water levels prior to and after rehabilitation during dry weather events, but such comparisons would not provide an accurate picture of the situation as the share of I/I-water is likely to be higher during rainfall. Another approach may be to compare water flows before and after measures in a rehabilitation area, with a control area in which no interventions are made [15]. Using a control area gives a reference point which is independent of any precipitation events that may occur.

The purpose of this study is to examine the water volume measurements and calculate the share of I/I-water in the wastewater system in selected areas in Asker Municipality in Norway, both before and after implementing measures. The study also aims at assessing whether the introduced measures have had an impact on the level of I/I-water. In order to examine the impact of completed measures to prevent I/I-water, two control areas were included in the study. The main goal of the project is to test out the mentioned method to understand whether it can be useful on a general basis for this type of analysis for I/I-water.

2. Methodology

2.1. Study area

Asker Municipality is located southwest of Norway's capital, Oslo. Asker has seasonal variations with cold winters, heavy rain during spring and autumn, and dry summers.

Most of the wastewater system in Asker was built in the 60s and 70s and consists mainly of concrete pipes. The entire wastewater system is a separate system. Even so, the sewer network is acting more like a combined system. In 2017 the share of I/I-water amounted to about 60% of the total delivered amounts of water delivered to the wastewater treatment plant (WWTP) [9].

The strategies for the water and wastewater business in Asker are anchored in the master plan for water and wastewater services in Asker from 2017. In this plan, I/I-water was identified as one of the main challenges [16]. At a tactical level, the utility has defined several renovations- zones. Trying to combat the challenges posed by I/I-water, there have been implemented measures in several of these renovations-zones. Since the system is a 100% separate system, the main measure has been rehabilitation of sewer pipes- besides troubleshooting for fault connected stormwater. Three of these rehabilitation areas are assessed in this study; Dæli, Vakås and Vestre vei. The areas are selected based on previous assessments on I/I-water, which indicates that the areas contribute to a large extent to the high level of I/I-water in the utility. The rehabilitation areas and the sewer system in Asker are shown in Figure 1. The locations of two rain gauges are also marked in Figure 1, along with the two areas used as control areas.

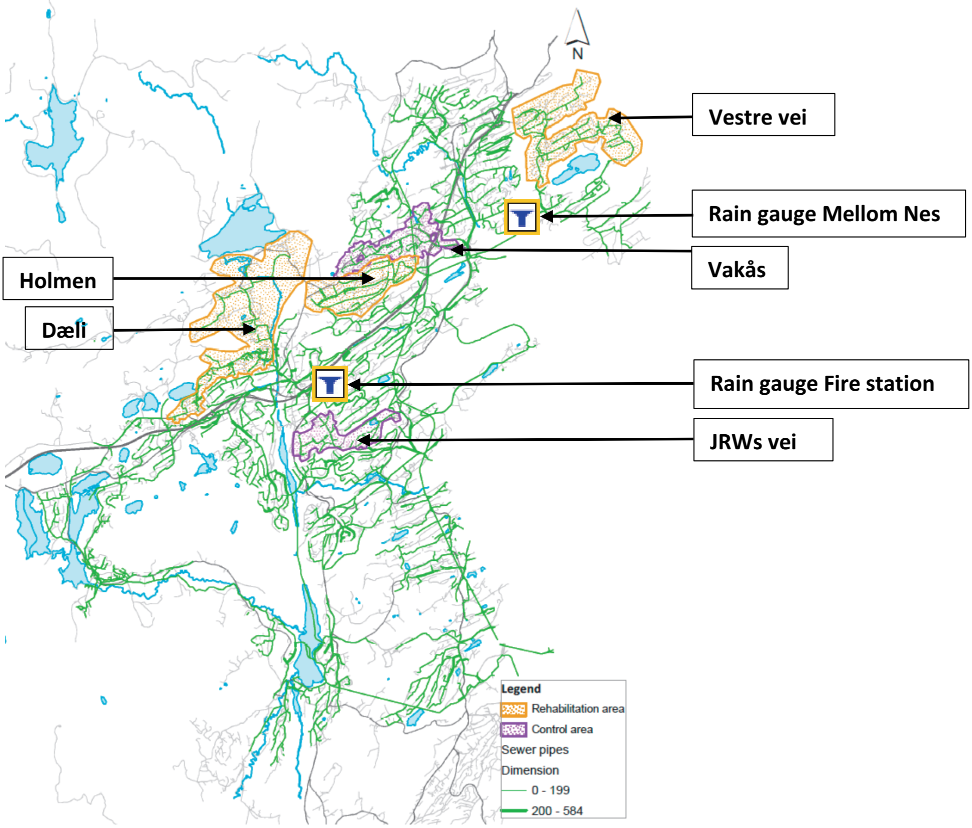

Figure 1: Overview map of the investigated areas as well as rain gauge locations

Prior to the rehabilitations, in 2015/2016/2017 respectively, water flow meter were installed in the rehabilitation areas and the control areas. The first area in which measures were implemented was Dæli. Vakås is an area where - as of 24.11.2020 - rehabilitation is ongoing but many measures have already been implemented. Measures were implemented in the Vestre vei area in 2019. J.R.Wilhelmsens vei (JRWs vei) and Holmen are included as control areas, as no measures were implemented in those areas during the time periods covered in this study. All assessed areas are residential areas with no industrial activity. The calculations do not account for commuting.

There are no overflow points in JRWs vei, Dæli and Vakås, while there are overflow points associated with sewage pumping stations in Holmen and Vestre vei.

There is no tradition of measuring the groundwater table in Asker so there is no data on how the wastewater discharges are affected by ground water.

2.2. Method to assess the effect of rehabilitation

To investigate the impact of the renovations, water flow levels and I/I-water volumes were examined and compared under different weather conditions, including both dry and wet weather events. Rehabilitated areas were examined and compared to the control areas before and after the rehabilitation.

Figure 2 illustrates the method utilized to investigate the impact of the renovations.

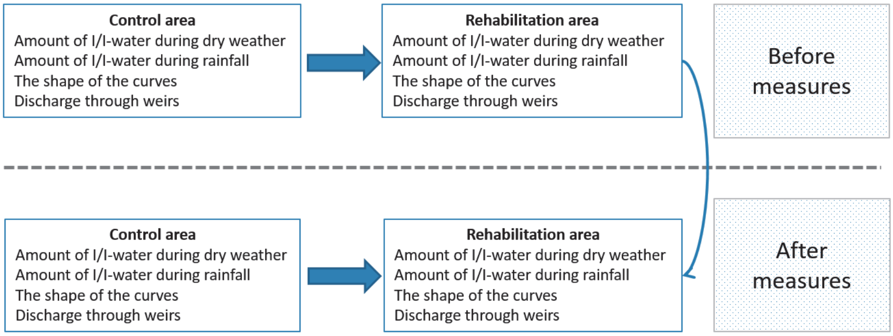

Figure 2: Schematic drawing of the method used to investigate the impact of measures in the rehabilitation areas

In order to do the evaluation of effect from the rehabilitation it is essential to obtain reliable flow data from all areas.

2.3. Measuring equipment

In the analyses conducted for this study, data were retrieved from two rain gauges located in Asker. These gauges have been in operation since March 2015 (Mellom Nes) and March 2016 (Asker Fire station) [17]. Days with missing data were omitted from the study.

Use of flow data is central in the presented study. Water flow gauges were installed in the wastewater pipeline network in all five zones in 2015/2016.

Several conditions need to be met to achieve reliable flow data. The pipe in which the meter is installed should be straight without bends or swells. The water flow should be as steady as possible, meaning that the pipe should maintain a steady and limited incline and not intersect with feed pipes. Experiences from Asker Municipality in Norway suggest that the ideal water flow rate for measurements is around 2 l/s. Normally, flows of 2 l/s correspond to areas servicing 1000 PE, which is a relatively large area. The limited sensitivity of current measurement technology makes it difficult to get good data from smaller drainage areas. Generally, pipeline renovations are conducted on small segments of the pipeline system, usually where the need is considered the greatest. Since such a large area is required to get reliable water flow measurements, the share of rehabilitated water pipes will be relatively small compared to the total pipe length within the area observed. It might therefore be challenging to accurately identify the impact of renovations applying water flow measurements. Another challenge is that even though a renovated part of the pipeline has become watertight, the water may travel along the outside pipe wall and infiltrate further down where the pipeline is not renovated.

The water flow meters used are intended to log data continuously. However, there are often operational outages that disrupt the data series. Since timeouts are relatively common in the time series, it can be difficult to find periods with reliable measurement data for several areas at the same time. This poses a challenge to comparing measurements from different areas. Conducting extended measurement periods is, therefore, crucial to obtain reliable data that can be used in comparative studies. The series selected for this study meets de above mentioned criteria.

Overflow meters were installed at two overflow points, one in the Holmen area and one in the Vestre vei area. The measuring devices that register overflow operation include two electrode sensors. Once the water level in the manhole rises to a level above the sensors, the salt in the water will conduct electricity and result in contact between the sensors. This contact persists until the water level falls once more in the manhole and the overflow operation ceases [18]. The unit used for measuring overflows is minutes of occurring discharge.

2.4. Calculation method

In the calculations performed in this study, measured water flow was used to calculate the share of I/I-water by using the water balance method. The calculations utilize a stipulated daily water consumption of 140 l/PE. The water balance method is shown in formula (1) [9, 13]:

$$(\%\ \text{share of I/I-water}) = (Q_{tot} - PE \times Q_{ap}) / (Q_{tot}) \times 100 \qquad (1)$$

Where:

I/I = I/I-water in the wastewater system [%]

Qtot = total amount of water transported to the measuring point [l/day]

PE = the number of persons situated within the catchment area

Q_{ap} = the amount of wastewater each person produces a day [l/pe day]

2.5. Description of the selected catchments

Characteristics the sewer pipes and drinking water pipes in Dæli, Vakås and Vestre vei are shown in Table 1.

Table 1: Characteristics of the wastewater and drinking water systems in Dæli, Vakås and Vestre vei

Area	Total length of waste-water pipes (m)	Number of PE	Rehabilitated sewer pipes		Total length of drinking water pipes (m)	Rehabilitated drinking water pipes		Rehabilitated manholes (sewer)	
			Meters rehab.	% of total		Meters rehab.	% of total	Number	% of total
Dæli	12,000	3,000	1,500	13	10,500	300	3	27	12
Vakås	9,500	2,000	1,000	11	11,300	1,300	12	18	13
Vestre vei	15,000	3,000	1,000	7	11,300	0	0	24	10

The municipality has a strategy to order rehabilitating of all private sewer pipes connected to the municipal sewer pipes that are being rehabilitated. This is a time-consuming process. In the assessed rehabilitation areas, no private pipes have been rehabilitated before the data used in the study were extracted.

The control areas are smaller than the areas they are compared to in terms of the number of inhabitants and the total length of the pipes. JRWs vei (control area to Dæli and Vakås) consist of 1,000 PE, while Holmen (control area to Vestre vei) consist of 1,500 PE. All areas are residential.

In Vakås, it is common for streams in several locations to affect the flow of water in the wastewater pipeline system. In Dæli, the rehabilitation work was initially prompted by surface water that had been erroneously connected to the wastewater pipeline system. In the catchment area by Vestre vei, frequent overflow runoff necessitated the redevelopment of wastewater pipelines in the zone. In all the rehabilitated areas, primarily old concrete pipelines have been rehabilitated. The rehabilitation methods vary between areas. In Dæli and Vestre vei, the work mainly entailed sliplining, while Vakås required full excavations and replacement of the concrete pipes with new pipes of PVC. Manholes were fully replaced in Vakås, while in Dæli and Vestre vei limited work was performed on manholes, with some manholes being fully encased in Vestre vei. In Vakås several wrongly connected stormwater pipes where discovered, but none of these were corrected by the time of data collection. In Vakås parts of the sewer system is situated near a small stream.

3. Results and discussion

3.1. Flow before implementation of measures

Dæli and Vakås

Figures 3 and 4 shows dry weather periods and rainfall periods prior to the implementation of measures. The figures show the percentage of I/I-water in the total measured water flow. Even though the entire wastewater system is a separate system, we find a large portion of I/I-water.

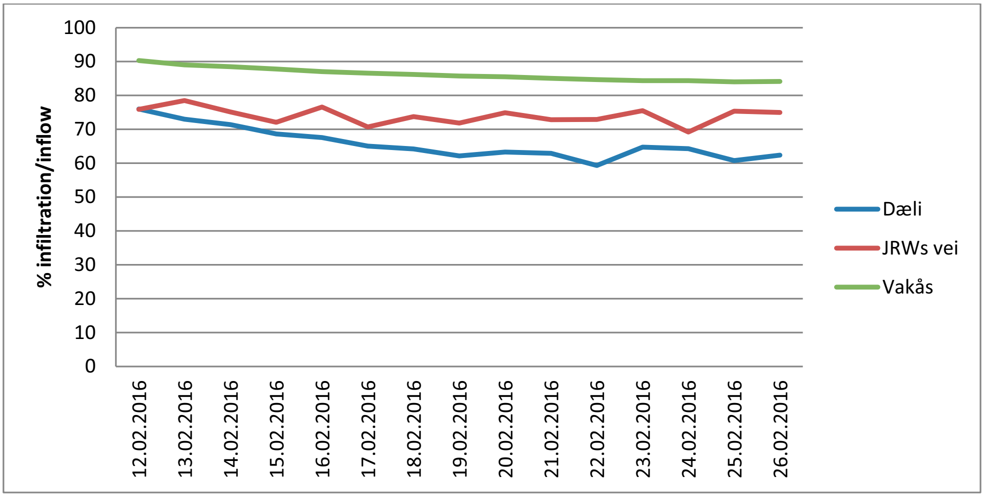

Figure 3: Calculated share of I/I-water in a dry weather period, before implementation of measures

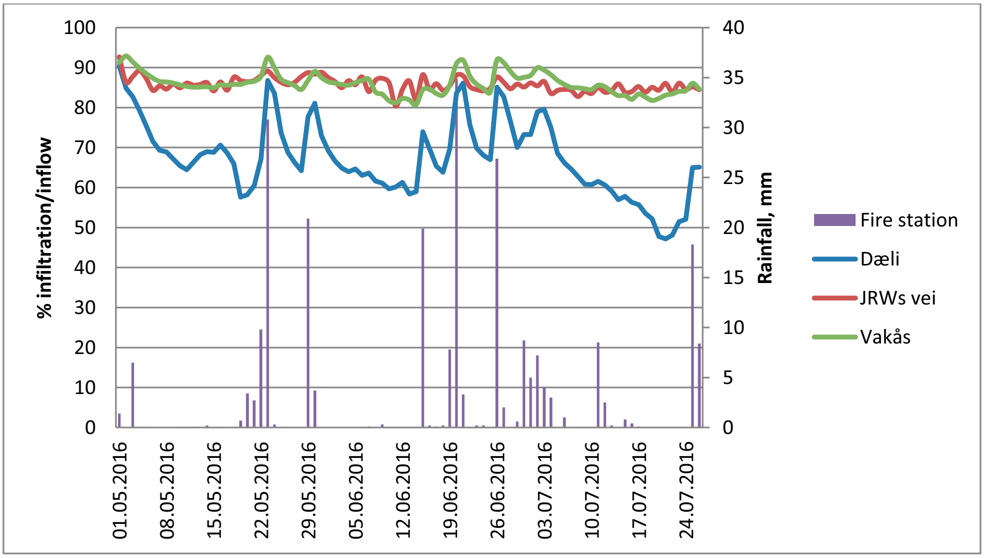

Figure 4: Calculated share of I/I-water in a wet weather period, before implementation of measures

For Vakås the share of I/I-water varied between 84% and 91% during the first half of 2016. In JRWs vei, the share of I/I-water varied between approximately 69% and 79%, while the share of I/I-water in Dæli ranged between approximately 59% and 76%. Despite an 11-day long dry period (3/5 - 11/5), the data reveal a large share of I/I-water in the wastewater system. In Vakås, the wastewater pipelines traverse a river at several points which is a likely contributor to the high shares of I/I-water. This is also likely to contribute to a high groundwater level at some points of the traverse.

The summer months of 2016 also saw relatively high levels of rainfall. The measured water flow in Dæli shows that the area was heavily affected by rainfall as the proportion of I/I-water peaked during precipitation events, while JRWs vei and Vakås had a consistently high proportion of I/I-water. Vakås and JRWs vei are presumably affected by I/I-water to such a degree that the levels remained generally high. Some of the reasons for this could include infiltration of river water, drinking water and groundwater. In Dæli, the variations in I/I-water are greater than in the other two areas. The share of I/I-water declines to approximately 50% in Dæli towards the end of the period. In other words, Dæli is quickly influenced by rainfall and dry weather alike, and the primary sources of I/I-water are presumably directly linked to surface water, and to a lesser extent infiltration.

Holmen

Figure 5 shows a dry weather period in the summer of 2018. No rainfall was registered during the entire period, meaning that the peak shown for 4666-Holmen must be due to factors other than rain. Most likely the meter was out of order this day. Another option is that the meter was temporary covered with particles and sludge. Approximately 30 mm of rainfall occurred during three days before the assessed dry weather period.

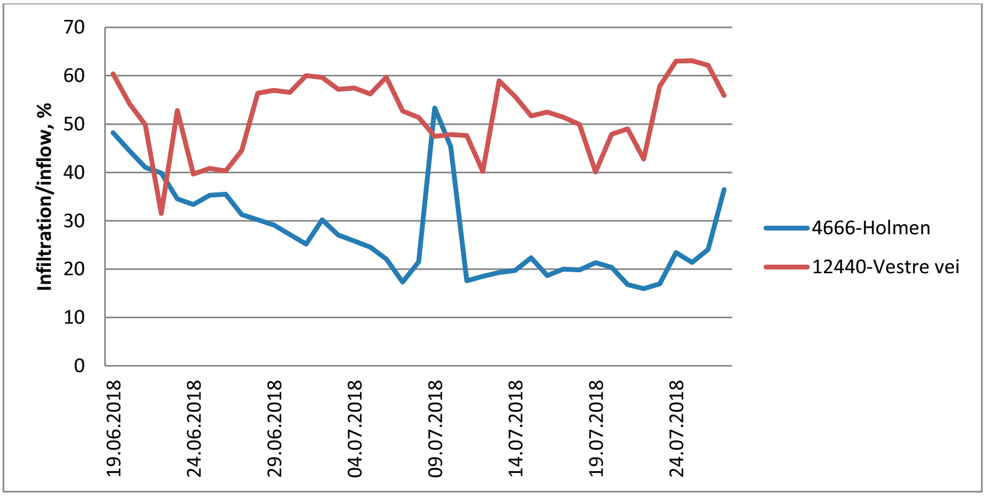

Figure 5: Calculated share of I/I-water in a dry weather period, before implementation of measures

In the period from 22.06.2018, the proportion of I/I-water in Vestre vei was higher than in Holmen. The minimum level in Holmen was 16%. The minimum level in Vestre vei was around 40%.

Figure 6 shows different rainfall periods before implemented measures.

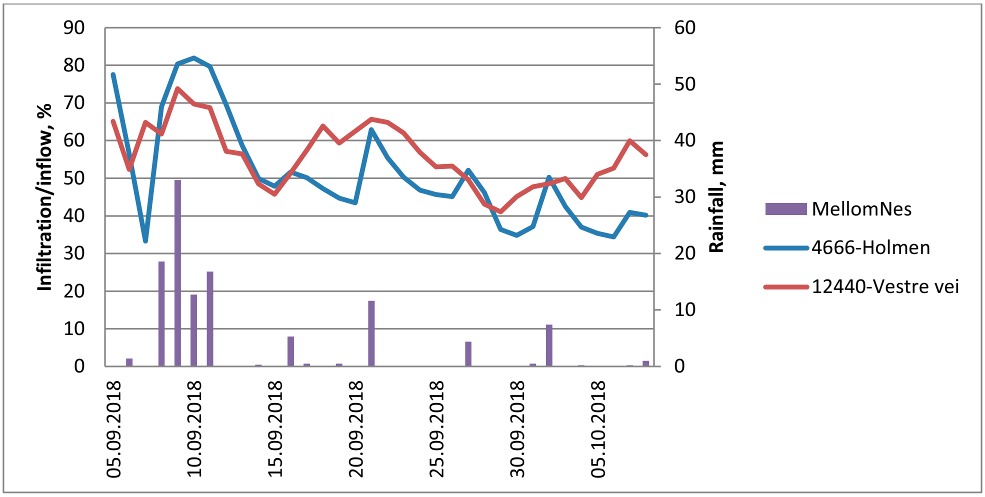

Figure 6: Calculated share of I/I-water in Holmen and Vestre vei in a wet weather period, before implementation of measures

There is no clear pattern during rainfall periods with regards to which site has the highest rates of I/I-water. Both areas are clearly influenced by rainfall. In Figure 6, we can see that the two areas are roughly similarly impacted by rainfall. Holmen has the highest volumes of I/I-water in the first part of the period, while Vestre vei has the highest volumes in the latter part of the period. The highest rainfall quantities came in the first part of the period.

By looking at rainfall in conjunction with the estimated share of I/I-water for all periods, the volumes of I/I-water are greatest in the Holmen zone during high precipitation periods. Holmen is impacted more slowly by rainfall than Vestre vei. Despite that, dry weather readings show that the share of regular infiltration is greatest in Vestre vei.

3.2. Flow after implementation of measures

Dæli and Vakås

Figure 7 shows the calculated share of I/I-water during a dry weather period - winter 2017 - after the implementation of measures in both Dæli and Vakås.

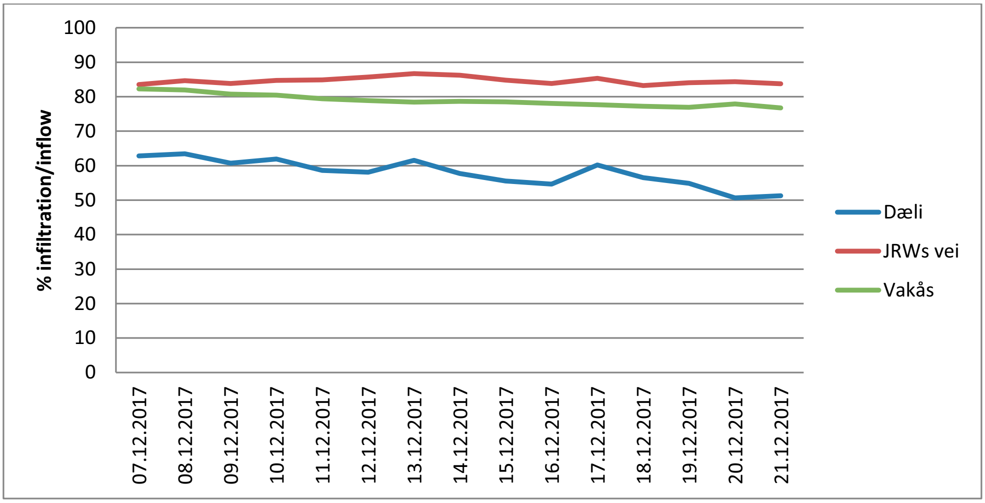

Figure 7: Calculated share of I/I-water in all three areas during a dry weather period, after implementation of measures

In this period, JRWs vei was the area with the highest share of I/I-water, between 82% and 87%. In the Vakås area, the share varied between 77% and 82%, while the share in Dæli varied between an estimated 51% and 63%.

Figure 8 shows the proportion of I/I-water in all three zones during rainfall after the implementation of measures.

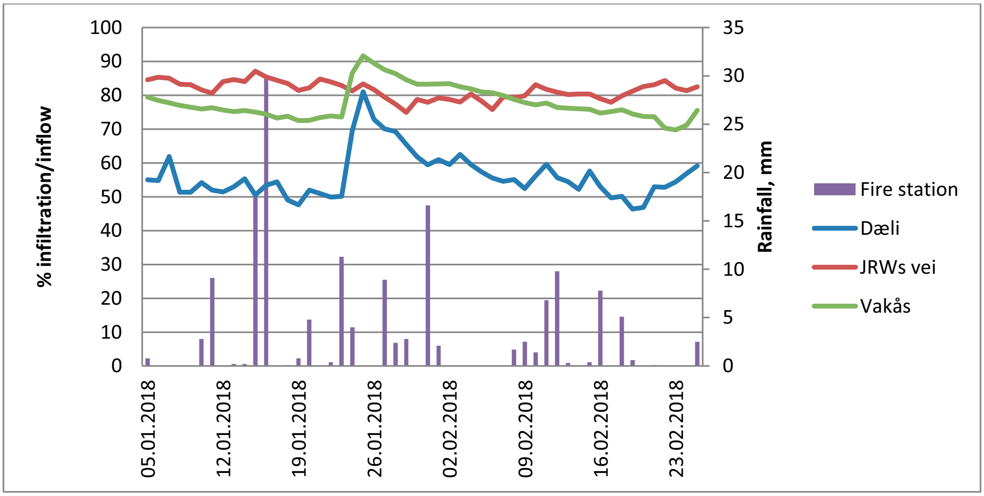

Figure 8: Calculated share of I/I-water in all surveyed points during rainfall,l after implementation of measures

Figure 8 shows that the I/I-water share in JRWs vei remains quite stable at approximately 80%, regardless of rainfall levels. Both the Dæli area and Vakås area are clearly influenced by rainfall. For

Vakås, the share varies between roughly 70% and 91%. The share of I/I-water in the Vakås area is generally lower than the corresponding share in JRWs vei. For Dæli, the share of I/I-water lies between 47% and 83%. In Figure 3 and 4 we saw that the Vakås area was the area with the highest level of I/I-water. However, in Figure 7 and 8, we see that for most of the time JRWs vei is the area with the highest share of I/I-water.

<u>Holmen</u>

Figure 9 shows the estimated share of I/I-water in a dry weather period after implementation of measures in the Holmen area. The period before the examined dry weather period was relatively wet with approximately 74 mm of rainfall over 11 days, which is the reason for the high share of I/I-water at the start of the period.

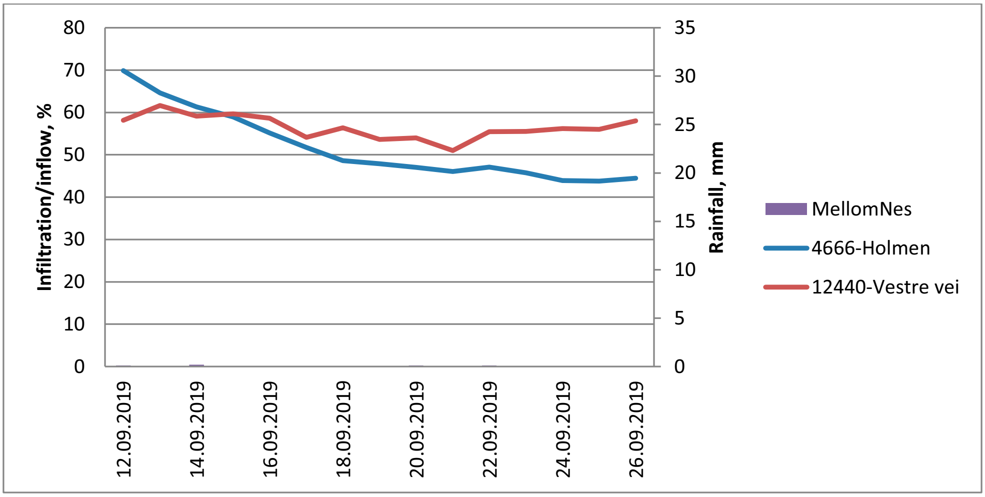

Figure 9: Calculated share of I/I-water in a dry period, after implementation of measures

The lowest estimated I/I-water level in Vestre vei is around 50%. In Holmen, the lowest level is around 44%. The share of I/I-water in the Vestre vei zone is generally higher than in Holmen. The share of I/I-water for the Holmen zone is thus higher during this period than in the period prior to completed measures in Vestre vei. The share of I/I-water in Vestre vei remained rather stable before and after the implementation of measures.

Figures 10 shows the share of I/I-water in Holmen and Vestre vei in different rainfall periods after implemented measures.

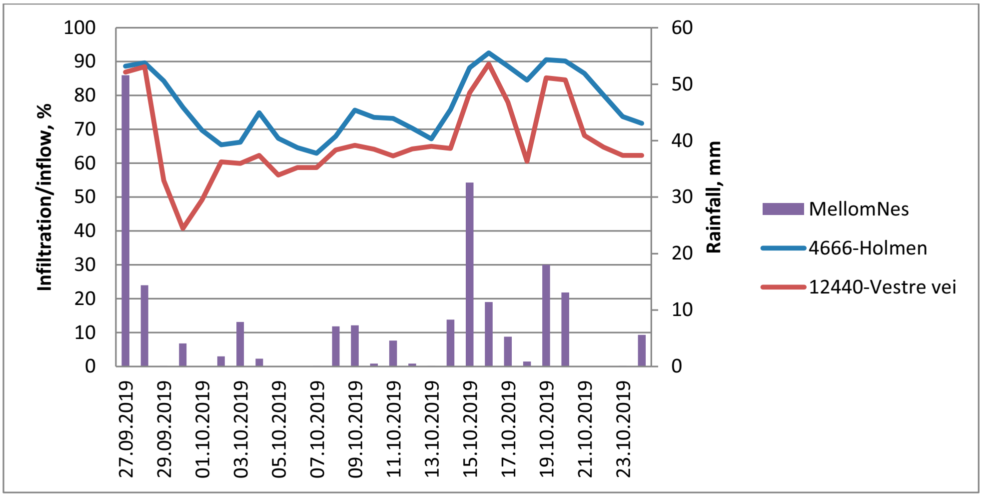

Figure 10: Calculated share of I/I-water during rainfall periods, after implemented measures

During all rainfall events we can see that the share of I/I-water is larger in Holmen than in Vestre vei. In Holmen, the share of I/I-water varies between 63% and 93%. In Vestre vei, the share varies between 40% and 89%. Similarly to prior to the implementation of measures, the volumes measured after implementation are larger in Holmen than Vestre vei. It still takes more time for the share of I/I-water to decrease in the Holmen zone than in the Vestre vei zone, after a rainfall has ended.

3.3. Comparisons of level of I/I-water

Extracted and considered periods with levels of I/I-water for all areas are shown in tables 2 and 3.

Table 2: Comparison between JRWs vei and the Vakås area and JRWs vei and Dæli, before and after implementation of measures, for different dry weather periods and different rainfall periods

dry weather

	before rehab. (12.02.2016-26.02.2016)	after rehab. (04.05.2018-13.05.2018)	change
JRWs vei (control area)	74%	78%	+4 ↑
Vakås (rehab. area)	86%	81%	- 5 ↓
Dæli (rehab. area)	66%	70%	+4 ↑

	before rehab. (12.02.2016-26.02.2016)	after rehab. (16.05.2018-27.05.2018)	change
JRWs vei (control area)	74%	74%	0 →
Vakås (rehab. area)	86%	64%	- 22 ↓
Dæli (rehab. area)	66%	61%	- 5 ↓

	before rehab. (31.08.2016-10.09.2016)	after rehab (04.05.2018-13.05.2018)	change
JRWs vei (control area)	85%	78%	- 7 ↓
Vakås (rehab. area)	85%	81%	- 4 ↓
Dæli (rehab. area)	63%	70%	+7 ↑

	before rehab. (31.08.2016-10.09.2016)	after rehab. (16.05-2018-27.05.2018)	change
JRWs vei (control area)	85%	78%	- 7 ↓
Vakås (rehab. area)	85%	64%	- 21 ↓
Dæli (rehab. area)	63%	61%	- 2 ↓

rainfall

	before rehab. (18.05.2016-01.06.2016)	after rehab. (04.05.2018-13.05.2018)	change
JRWs vei (control area)	87%	82%	- 5 ↓
Vakås (rehab. area)	87%	79%	- 8 ↓
Dæli (rehab. area)	70%	58%	- 12 ↓

	before rehab. (18.08.2016-02.09.2016)	after rehab. (07.02.2018-25.02.2018)	change
JRWs vei (control area)	86%	81%	- 5 ↓
Vakås (rehab. area)	88%	75%	- 13 ↓
Dæli (rehab. area)	68%	54%	- 14 ↓

Table 3: Comparison between Holmen area and Vestre vei area for share of I/I-water before and after implemented measures for different for different dry weather periods and different rainfall periods

dry weather				rainfall			
	before rehab. (08.12.2017-25.12.2017)	after rehab. (06.08.2019-09.08.2019)	change		before rehab. (05.11.2017-10.11.2017)	after rehab. (28.08.2019-29.08.2019)	change
Holmen (control area)	45%	48%	+3 ↑	Holmen (control area)	62%	67%	+5 ↑
Vestre vei (rehab. area)	46%	60%	+14 ↑	Vestre vei (rehab. area)	37%	64%	+27 ↑
	before rehab. (29.05.2018-09.06.2018)	after rehab. (06.08.2019-09.08.2019)	change		before rehab. (28.07.2018-12.08.2018)	after rehab. (10.08.2019-12.08.2019)	change
Holmen (control area)	69%	48%	- 21 ↓	Holmen (control area)	37%	75%	+38 ↑
Vestre vei (rehab. area)	56%	60%	+4 ↑	Vestre vei (rehab. area)	62%	57%	- 5 ↓
	before rehab. (19.06.2018-08.07.2018)	after rehab (15.09.2019-19.09.2019)	change		before rehab. (05.09.2018-11.09.2018)	after rehab (27.09.2019-04.10.2019)	change
Holmen (control area)	31%	51%	+20 ↑	Holmen (control area)	68%	77%	+9 ↑
Vestre vei (rehab. area)	52%	56%	+4 ↑	Vestre vei (rehab. area)	65%	63%	- 2 ↓

The reduction in I/I-water for the areas of Vakås, Dæli and Vestre vei are summed up as follows:

- Vakås: Dry weather = 9-22 % points, Rainfall: 3-8 % points
- Dæli: Dry weather = 0 Rainfall: 7-9% points
- Vestre vei: Dry weather = 0 Rainfall: 11-43% points

The results presented above are based on the following prerequisite: The assessed rain events occur after a minimum of three days of dry weather. This comparison neither takes into account rainfall conditions before the event in question nor has the temperature in the compared periods been taken into account.

Comparisons between the control areas and rehabilitation areas in dry weather suggest that while the I/I-water quantities declined in the Vakås area, it is difficult to see whether the measures implemented in the Dæli and Vestre vei areas have had any impact. Comparisons between control areas and the rehabilitation areas suggest that the measures have had an effect on the level of I/I-water during rainfall for Vestre vei, but the reduction is only minor for Vakås and Dæli.

3.4. Comparisons of overflow operations

In addition to examining the pipe flow readings, overflow operation in Vestre vei and Holmen (control area) have been examined. Figure 11 displays overflow operation and rainfall readings from the rain gauges at Mellom Nes and the Fire station both before and after implementing measures.

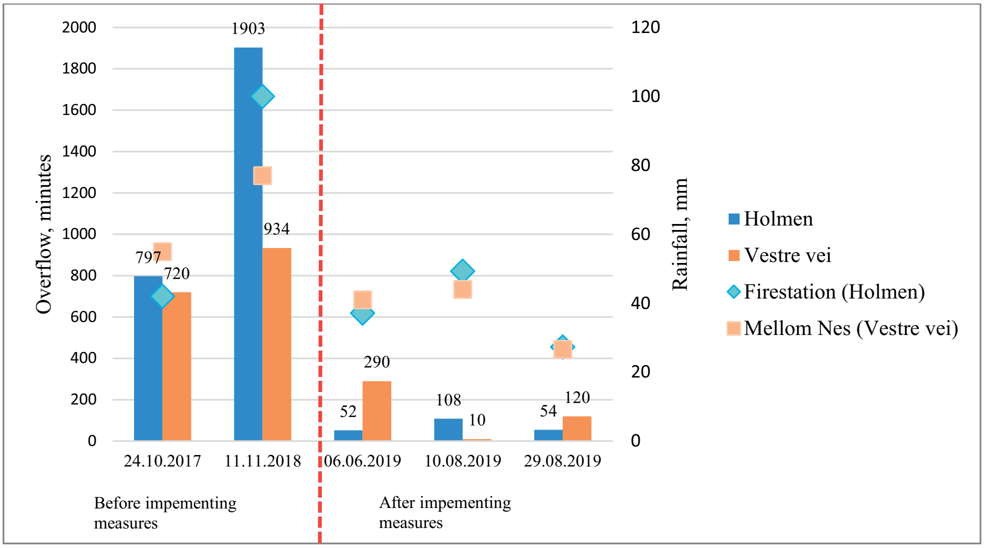

Figure 11: Registered overflow at Holmen and Vester vei and rainfall at the fire station and Mellom Nes

After implementation of measures, in two out of three of the events, overflows last longer in Vestre vei than in Holmen. On 10.08.2019, overflow lasted longer in Holmen than in Vestre vei. The explanation for this is that it likely rained more in Holmen's influx area than in Vestre vei's influx area. Before the implementation of measures, the Holmen zone was most sensitive to overflows, while Vestre vei was more sensitive to overflows after the implementation of measures. This is the opposite result of what one would expect.

By considering overflow operation solely in the rehabilitation area of Vestre vei, it looks as there has been a reduction in overflow operation after the implementation of measures. However, including overflow operation in Holmen, where no such measures have been implemented, we can see a clear reduction there too. In other words, we cannot prove a reduction in overflow operation in Vestre vei as a result of pipe rehabilitation.

4. Conclusion

The main conclusion of this study is that rehabilitating only small proportions of pipelines and manholes, give a small but not proportional reduction in I/I-water. Rehabilitating small portions of the pipelines with the sole reason of reducing I/I-water cannot be recommended. Achieving larger reductions in I/I-water will presumably require the rehabilitation of a much larger share of the pipelines than done in this study.

In the studied areas the level of I/I-water is high even though all these areas have a 100% separate system. One common way to combat I/I-water in areas with separate system is to rehabilitate the parts of the pipeline identified to be in bad condition through CCTV inspection. The rehabilitation projects that have been carried out in this study cover between 7% and 13% of the total municipal wastewater pipelines within the selected study areas. In the investigated areas rehabilitation of sewer pipes has shown only limited results.

The only area where there is a reduction of I/I-water in dry weather is Vakås. This is also the only area where the renovation method has been a full replacement of both pipes and manholes, and a replacement of drinking water pipes as well. Since the Vakås area is under the influence of a stream, and therefore also groundwater, it is likely to assume that this is the source being reduced during dry weather.

The data from Vakås and Dæli suggest that the share of I/I-water decreased slightly in both areas during rainfall. By looking at data collected during precipitation events before and after the implementation of measures, and by ranking the areas against each other by the share of I/I-water, we see that the area rankings changes. Prior to the implementation of measures, Vakås was the area with the highest share of I/I-water. Yet, afterwards, JRWs vei (the control area) was the area with the highest share of I/I-water. In Vakås, the reduction in the influx of I/I-water ranged between 9 percentage point to 22 percentage points in dry weather periods and 3 percentage point to 8 percentage points in rainfall periods. It is difficult to prove the impact of measures in dry weather periods in Dæli, but for rainfall periods the implemented measures have likely resulted in a 7 - 9 percentage points reduction in I/I-water.

As for Vestre vei, there has likely been zero reduction in I/I-water in dry weather conditions, while the reduction in rainfall periods is somewhere between 11 and 43 percentage points. We were unable to prove any significant reductions in overflow operation time in the rehabilitation area Vestre vei after the implementation of measures.

Every manhole is a puncture of the piping system. By including manholes in the wastewater system we allow the I/I-water to enter the system at numerous weak points. It should be investigated to what extend a full replacement of manholes alone, not in combination with the renovation of pipes, will reduce the level of I/I-water. Whatever measure is chosen the effect of the investments should always be evaluated.

The scope of the presented study was to investigate what effect rehabilitation of municipal pipes have on I/I-water. It is recommended to perform a new study when the rehabilitation of private pipes is completed. It is also recommended to start a groundwater level measurement programme in different parts of the municipality to find out how the groundwater influences the level of I/I-water.

Due to the results in this study, it is clear that indicators aiming at documenting the condition and functionality of the sewer system should be chosen carefully. It may seem that an indicator looking at renovation rate may be misguiding when used to assess the functionality of the pipes. Even when investing large sums of money in renovating pipes, this may not improve the functionality of the system.

Evaluating the impact of measures to control I/I-water is challenging. Because the volumes of I/I-water are so closely related to rainfall, it can be difficult to find two similar - and thus comparable - situations before and after the implementation of measures. Even if two or more rainfall periods have equally high volumes of rainfall, the ratio rainfall/dry weather before those periods will affect the results. To get around this challenge, the proposed method of comparing results from a project area with a control area where no measures have been implemented may be appropriate. This was done successfully in this study. The method requires long data series of pipe flows and precipitation, which in and of itself can pose challenges. In the data used for this study, there have been frequent timeouts. The use of water flow measurements to evaluate I/I-water, requires close monitoring of the measuring devices.

Acknowledgments

The authors want to thank Asker municipality for willingly sharing information and for giving access to data. The authors also want thank Asker municipality and the Research Council of Norway for financing this study, and Rita Ugarelli for important input and help.

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ISBN: 978-82-575-1807-3
ISSN: 1894-6402

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