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Indhold

Forord

Denne rapport er udarbejdet på baggrund af projektet ”Mere vand fra skove - nye virkemidler til vandplanerne”, der er gennemført med tilskud fra Miljøministeriet, bevilliget 2011.

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I følgegruppen har, udover projektgruppen, også Naturstyrelsen deltaget v/geolog *Susanne Hartelius* (2012) og forstfuldmægtig *Robert Jensen* (2013). Desuden deltog HOFOR (tidl. Københavns Energi A/S) v/miljøteknikker *Jens Rasmussen* og sektionsleder *Anne Scherfig Kruse,* samt adj. professor *Merete Styczen*, Institut for Plante- og Miljøvidenskab (PLEN), KU.

To projektstuderende *Bo Pang*, IGN, KU og *Antoine Bruge*, GEUS og Ecole des métiers de l’environnement, Aix-Marseille Universitet, Frankrig, udførte deres kandidatprojekter i forbindelse med projektet. De har således bidraget med detaljerede analyser og ny aspekter, som ellers ikke ville være blevet gennemført.

Projektgruppen vil hermed rette en særlig tak til professor *Merete Styczen* for hendes engagement i idefasen, faglige indspark i projektet og detaljerede kommentarer til rapporten.

Sammenfatning

Vandressourcen på Sjælland og omkring de større byer er under pres. Oppumpning af drikkevand sænker grundvandsstanden og giver for lav vandføring i vandløbene. Da nåleskov har større vandforbrug end løvskov (med en forskel på 115 mm/år), kan konvertering fra nåleskov til løvskov måske bidrage til at øge vandressourcen på Sjælland eller andre steder. Denne rapport beskriver modelberegninger på oplandsskala der illustrerer betydningen af træart og forskellige arealanvendelser for grundvandsstand og vandløbsvandføring.

For at kunne beskrive vandbalancen korrekt for nåle- og løvskov blev et fordampningsmodul (SVAT-modul) til oplandsmodellen MIKE SHE kalibreret til måleserier for gennemdryp og jordfugtighed fra danske rødgran- og bøge-bevoksninger. Dette resulterede i en række vegetationsparametre for rødgran og bøg, der kombineret med litteraturværdier for energipil og forskellige landbrugsafgrøder (græs, vinterhvede, byg og majs) gav mulighed for at sammenligne vandbalancer for alle disse vegetationstyper. Fordampningen fra de forskellige vegetationstyper varierede over året styret af udspring, vækstperiode og bladareal. Fordampningen var størst fra rødgran på grund af et stort interceptionstab fra nålene gennem hele året, mens den var mindst fra majs, der har en sen og kort vækstsæson.

Oplandsmodellen MIKE SHE SVAT, der beskriver vandstrømme i jord og grundvand i 3D, blev opsat for to oplande (Skjern og Lejre) på henholdsvis sandjord i Jylland og lerjord på Sjælland. Med udgangspunkt i klimadata for en 10-årig periode for de to oplande blev en række scenarier for arealanvendelse (fx nuværende, nåleskov til løvskov, fordobling af skovarealet og nåleskov, løvskov eller landbrug overalt) simuleret og resultaterne for grundvandsstand og vandløbsvandføring sammenlignet. Ændringer i arealanvendelse, der medførte væsentlige ændringer i fordampning, gav betydelige ændringer i grundvandsstanden i det sandede Skjern-opland, mens ændringerne i det mere lerede Lejre opland først og fremmest resulterede i ændret vandløbsvandføring.

Modelresultaterne for konvertering af eksisterende nåleskov til løvskov i Lejre-oplandet gav lidt højere grundvandsdannelse således at det primære grundvandspejl steg med op til 50 cm over et større område med spredte skove. Minimumsvandføringen i et mindre vandløb fra samme område steg med 7% (1,2 l/s).

Med de udviklede modeller er det muligt at vurdere tiltag i skovrige oplande til drikkevandsboringer eller at vurdere den hydrologiske effekt af større skovrejsningsprojekter. Parameteriseringen af skov bør forbedres yderligere i oplandsmodellen især vedrørende beskrivelsen af dræning. Den nuværende beskrivelse af dræning i modellen er baseret på forholdene under landbrugsdrift, mens dræning i skove er mindre effektiv, derfor er den positive effekt af skov på opholdstid og vandløbsvandføring undervurderet.

Summary

The water resources in the capital region on Sealand and around other major cities in Denmark are under pressure. Abstraction of drinking water is lowering the groundwater and often leads to low stream discharge in these regions. Since coniferous forest have a higher water use than broadleaf forest (a difference of 115 mm/yr), conversion of existing coniferous forest to broadleaf forest may contribute to increase the water resource in these regions. This report describe hydrological modelling on a catchment scale illustrating the influence of tree type and various land use scenarios on groundwater level and stream discharge.

To describe the water balance correctly for coniferous and broadleaved forests an evaporation simulation module (SVAT) for the catchment model MIKE SHE was calibrated to measured hydrological time series from Danish spruce and beech stands. From this work a range of vegetation parameters for spruce and beech were obtained and combined with literature values for willow coppice and various agricultural crops (grass, winter wheat, barley and corn) to allow comparisons of water balance calculations for all these vegetation types. Evapotranspiration (ET) from the vegetation types varied with season controlled by phenology, growth period and leaf area. The ET was highest from spruce due to a large interception loss from the needles all year, whereas ET was least in corn due to its short and late growing season.

The catchment model MIKE SHE SVAT that describes water flow in soil and ground water in 3D was set up for two catchments (Skjern in Jutland and Lejre on Sealand) with sandy and clayey soils, respectively. A 10-year climate data record was used to simulate and compare the effect of land uses (e.g. current, coniferous forest converted to broadleaf, doubling of the forest area and total cover of coniferous forest, broadleaved forest or agricultural crops) on groundwater level and stream discharge.
Land use changes affecting ET lead to substantial changes in the groundwater level in the sandy Skjern catchment, while the same land use change in the clayey Lejre catchment mainly lead to changes in stream discharge.

Model results from simulating a conversion of current, coniferous forest to broadleaved forest in the Lejre-catchment showed a small increase in ground water recharge and the primary groundwater table was elevated by up to 50 cm over the catchment area with forest patches. Minimum stream discharge in the stream draining that area increased by 7% (1,2 l/s).

The developed models can be used to evaluate the hydrological effects of land use options in forest dominated drinking water catchments or the effects of major afforestation projects. However, the parameter sets and the descriptions of the forest land uses in the catchment model need further improvement. In particular the description of drainage, that currently rely on description of the conditions observed on agricultural fields, need to be improved to capture the less effective drainage of forests. Therefore the positive effect of forest land use on water retention time and stream discharge is underestimated.

1. Indledning

Motivation

Vandressourcer på dele af Sjælland er under pres (Henriksen & Troldborg 2003), hvilket medfører negative konsekvenser for en del vandløb hvor minimumsvandføringen om sommeren er kritisk lav (Naturstyrelsen, 2011). Der mangler også vand omkring Århus og andre af de større byer, men i væsentligt mindre grad end på Sjælland.

Med et skovdække på omkring 14% i Danmark, har der naturligt nok ikke været meget fokus på skovenes rolle i vandkredsløbet. I vandsektoren er skov og skovrejsning mest forbundet med mulighederne for sikring af vandkvaliteten. I forbindelse med skovrejsning har skovenes vandforbrug været diskuteret idet dette generelt er højere end for landbrug og anden lav vegetation (fx Verstraeten et al., 2005). Løsningen har været at satse overvejende på tilplantning med løvtræer, der har væsentligt lavere vandforbrug end nåletræer (Boks 1), for derved at ændre vandkredsløbet mindst muligt med de 'nye' skove.

Da det eksisterende skovareal i Danmark hovedsageligt er dækket af nåleskov med høj fordampning er der et betydeligt potentiale for at forøge vandressourcen i områder med skov ved at konvertere nåleskov til løvskov – et potentiale som ikke tidligere har været diskuteret eller bragt i spil i forbindelse med manglen på vand på Sjælland og andre steder. En ændring fra nål til løv kan under de rette omstændigheder øge nedsivningen til grund- og overfladevand med 115 mm/år, når klima og jordbundsforhold er ens (Boks 1). Statsskovene og mange private skove har planlagt udfasning af nåletræer over de næste 50 år, men en vurdering af denne udfasnings effekt på vandressourcen mangler. Ændret træartssammensætning i skovene kan derfor vise sig at være et potentielt virkemiddel til at øge nedsivningen, men er ikke nævnt i de nye vandmiljøplaner og heller ikke i regeringens "Handlingsplan for sikring af drikkevandskvaliteten 2010 - 2012" (By- og Landskabstyrelsen, 2010b).

Et simpelt overslag for skovarealet på Sjælland og Lolland-Falster, med omkring 30% nåleskov, viser at en fuldstændig konvertering af disse nåleskove til løvskov kan potentielt øge nedsivningen med omkring 40 mia. liter vand årligt af god kvalitet (Christiansen og Gundersen, 2011). Ved at vælge løvtræarter, f.eks. ahorn, med mindst fordampning (Boks 1) bliver potentialet endnu større. Denne forøgede nedsivning er lidt mindre end hovedstadsområdets årlige vandforbrug på 52 mia. liter (Københavns Energi, 2011) og modsvarer omtrent den mængde af vand der ifølge Vandplanerne for Sjælland skal findes ved flytning af eller etablering af nye boringer og oppumpning af grundvand til vandløb (By- og Landskabsstyrelsen, 2010a).

I dette projekt fokuserer vi derfor på mulighederne for i de eksisterende skove at generere mere grundvand af god kvalitet gennem ændringer i træartssammensætningen – 'skovene som virkemiddel i vandforvaltningen'. Dette er formentlig den eneste 'teknologi' der naturligt kan øge vandressourcen. Imidlertid er det de lokale hydrologiske og geologiske forhold, der bestemmer om nedsivningen vil bidrage til grundvandsdannelse eller til øget afstrømning i vandløb og åer. Det sidste kan vise sig fordelagtigt i områder præget af vandindvinding men uhensigtsmæssigt i områder med risiko for oversvømmelse, specielt set i lyset af en forventet øget vinternedbør som følge af klimaændringer.

At forudsige virkningen af ændringer i et konkret skovområde (eller ved skovrejsning) på henholdsvis grundvandsdannelse og afstrømning i vandløb kræver dog en detaljeret hydrologisk oplandsmodel. I et tidligere projekt SAVANNE konstaterede vi, at den hidtil anvendte oplandsmodel ikke var egnet til oplande med skov, især den høje fordampning fra nåleskov kunne ikke håndteres i modellen (Sonnenborg et al. 2009). Det er derfor nødvendigt at anvende (og videreudvikle) et avanceret værktøj til opgørelse af sammenhængen mellem arealanvendelse og vandbalancen, herunder vandføringen i vandløb.

Den hydrologiske model MIKE SHE (DHI, 2010) anvendes i dette projekt, da det er en af de mest avancerede, fleksible og anvendte modeller til beregning af det hydrologiske kredsløb på oplandsskala. Dette inkluderer en integreret modellering af hele vandkredsløbet, hvor fordampningen beskrives med en nyudviklet energibaseret beregning af fordampningen fra forskellige vegetationstyper (Soil-Vegetation-Atmosphere Transfer model, SVAT) (Overgaard, 2005). Denne SVAT-model i MIKE SHE er i forbindelse med dette projekt blevet parameteriseret for skov og energiafgrøder. Herved opnås en fysisk baseret beskrivelse af fordampningsprocesserne, som gør det muligt at differentiere mellem skovtyper og kvantificere effekten heraf på vandbalancen.

MIKE SHE modellen er derfor i stand til at integrere vandbalancen for vegetationen og den umættede zone med dynamikken i dybereliggende grundvandsreservoirer, hvilket er et krav for at formålet med dette projekt kan realiseres.

Formål

Vi ønsker at konkretisere ellers oversete muligheder for at øge vandressourcen gennem udnyttelse af træarternes meget forskellige vandforbrug. Projektets oprindelige formål var mere detaljeret formuleret som følger:

- at koble en avanceret beskrivelse af fordampning og den umættede zone med en integreret dynamisk model for grundvand og vandløb på oplandsbasis
- at implementere den nyeste viden om forskellige arealanvendelsers (skov, landbrug) påvirkning af grundvandsdannelse og overfladenære vandressourcer i modeller for to områder – et i det østlige og et i det vestlige Danmark, for derigennem
- at dokumentere konvertering af eksisterende nåleskove til løvskove som et nyt virkemiddel til at øge vandressourcen, således at det kan indgå i fremtidige vandplaners virkemiddelkatalog;
- at undersøge hvorledes tilplantning af landbrugsarealer med energiafgrøder, som pil og poppel, påvirker dannelsen af grund- og overfladevand.

Den langsigtede målsætning med projektet er at danne basis for et modelkoncept, der inkluderer og kvantificerer skovenes rolle (inklusiv energiafgrøder som pil og poppel) i vandkredsløbet på oplandsbasis. Det er ligeledes et mål med projektet at få bedre viden om påvirkningen på vandkredsløbet ved ændringer i arealanvendelsen i skoven og ved skovrejsning. Dette modelkoncept kan indgå i fremtidens kommunale og statslige forvaltning og indsats for områder med værdifulde drikkevandsressourcer, hvor skovenes udformning og placering kan spille en rolle.

Arbejdet

Arbejdet med projektet har omfattet en række modeltekniske trin og databehandling der kort kan sammenfattes til følgende:

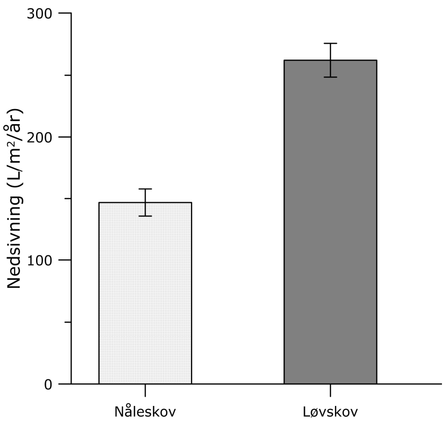
- Tilvejebringelse af datagrundlag for SVAT modellering: Tidsserier for gennemdryp og jordfugtighed m.m. fra to skovovervågningspunkter (Gludsted/Rødgran; Frederiksborg/bøg); fordampningsdata fra HOBE-projektet; tiårige klimadataserier med timeværdier; litteraturstudier vedr. energipil.
- Sensitivitetsanalyser, kalibrering af de udvalgte sensitive vegetationsparametre og validering af SVAT-modellen i MIKE SHE.
- Sammenligning og analyse af SVAT-modelresultater for vegetationstyper i forskellige situationer.
- Analyser af arealanvendelse i de udvalgte oplande (Skjern og Lejre). Udvikling af GIS værktøj til fremstilling af distribuerede arealanvendelsesscenarier med efterfølgende valg af scenarier.
- Redigering af MIKE SHE-opsætninger for de udvalgte oplande og implementering af arealanvendelsesscenarier, hvilket gav en del modeltekniske udfordringer.
- Gennemregning af en række arealanvendelsesscenarier i tiårige forløb (med forudgående ti års initialiseringsforløb for at sikre at modellen kommer i ligevægt med den 'nye' arealanvendelse).
- Udtræk af datalag til analyse og sammenligning af scenarier

Boks 1: **Træarter og nedsivning**

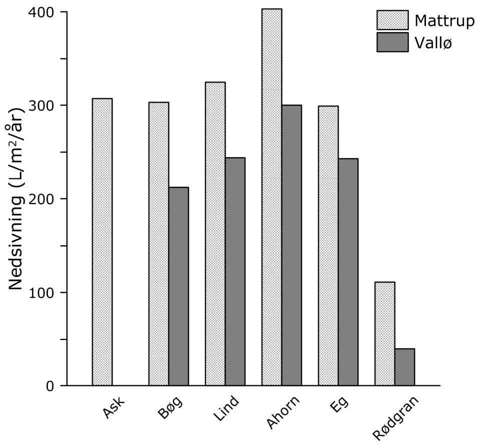
Nåletræer har generelt væsentlig højere fordampning end løvtræer, idet nåletræerne har en stor kroneoverflade hele året. Det er især det såkaldte interceptionstab, der er den afgørende årsag til forskellen. Interceptionstabet er den mængde vand, der bliver hængende i trækronen på blad- og grenoverflader efter en regnbyge er slut og når at fordamper fra overfladerne inden det kan dryppe ned på jordoverfladen.

Vandbalancen for bevoksninger af nåle- og løvtræer på samme lokalitet og jordbund er blevet sammenlignet i 7 forskellige studier på Sjælland og sammenfattet i figur 1. Forskellen i fordampning mellem gruppen af nåletræer (rødgran (4 lokaliter), andre granarter (2)) og gruppen af løvtræer (bøg (5), eg (4), andre (2)) giver anledning til *en forskel i nedsivning på 115 mm/år (liter/m²/år).* Forskellen gælder for højskov (ældre end 30 år) og inkluderer fx ikke fyrretræer. Forskellen på 115 mm/år er således ikke generel, men illustrerer de betydelige og fundamentale forskelle i vandkredsløbet mellem løvfældende og stedsegrøn vegetation.

Nedsivningen kan også variere betydeligt under forskellige løvtræarter med forskelle op til 100 mm/år ved samme alder (figur 2). Bevoksninger af ahorn (ær) har den største nedsivning, mens nærliggende bøgebevoksninger har den mindste nedsivning blandt fem almindelige danske løvtræarter (figur 2).



Figur 1: Nedsivning under nåle- og løvskov på sammen lokalitet, gennemsnit af 7 studier på Sjælland. Beregninger foretaget med forskellige 'søjlemodeller' for bevoksninger ældre end 30 år.



Figur 2: Nedsivning (L/m²/år) fra forskellige træarter i henholdsvis Mattrup, vest for Horsens, (lysegrå) og Vallø, syd for Køge (mørkegrå). Højere nedsivning i Mattrup skyldes højere nedbør (Christiansen m.fl. 2010).

Denne rapport

Det modeltekniske arbejde og resultaterne fra en række gennemregnede scenarier for arealanvendelse er dokumenteret i to udkast til 'peer-review' artikler på engelsk. Den første artikel (Bilag 1) omhandler arbejdet med opsætning af fordampningsmodellen (SVAT) for de forskellige skovtyper og (energi) afgrøder (kalibrering og validering af vegetationsparametre) og analyse af modellens estimater for fordampning og nedsivning for forskellige typer af vegetationsdække. Den anden artikel (Bilag 2) omhandler arbejdet med oplandsmodellen (MIKE SHE SVAT) og viser resultaterne af arealanvendelsesscenarier med forskellige grader af skovdække med henholdsvis nåle- og løvtræer (rødgran og bøg) samt med energiafgrøder (pil).

Frem for at sammenfatte alle resultaterne fra de to detaljerede bilag har vi valgt at fokusere denne rapport på den oprindelige problemstilling der motiverede arbejdet: Hvad er effekten af konvertering af nåleskov til løvskov på bevoksnings- og oplandsskala bl.a. med henblik på om dette kan bidrage til at afhjælpe vandmanglen på Sjælland? Det efterfølgende kapitel behandler denne problemstilling i form af et udkast til en artikel til et dansk fagtidsskrift overvejende rettet mod den skovbrugsfaglige sektor. De modeltekniske resultater, oplandsmodelen og sammenligning af vandbalance ift. arealanvendelse blev præsenteret for vandsektoren ved årsmødet i Danish Water Forum (Pang m.fl., 2014).

2. Får vi mere vand når nåleskov bliver til løvskov?

(Formuleret som oplæg til artikel i et fagtidsskrift fx Skoven)

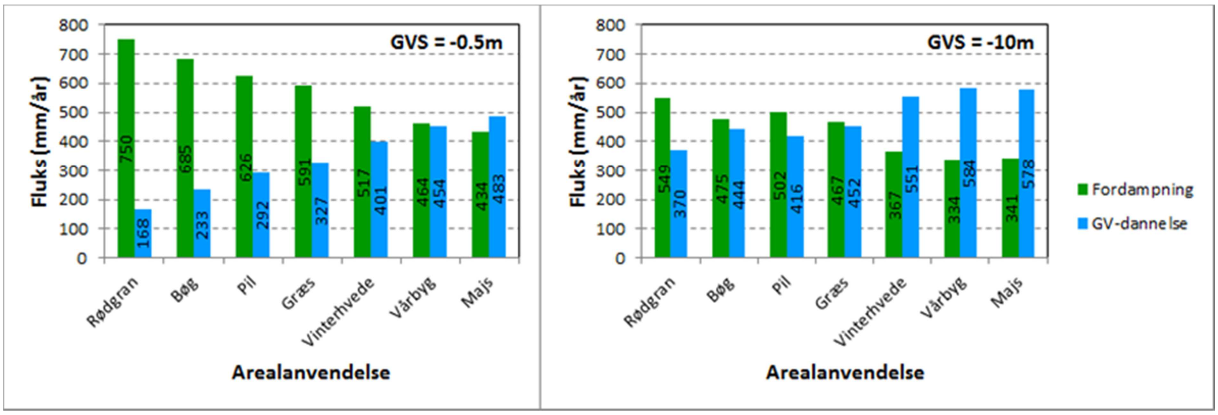
Vandressourcen på Sjælland er under pres. Oppumpning af drikkevand giver bl.a. for lav vandføring i vandløbene. Da nåleskov har større vandforbrug end løvskov, kan konvertering fra 'nål til løv' måske bidrage til at øge vandressourcen på Sjælland. Vi har udført modelberegninger på oplandsskala for at illustrere betydningen af træart m.m. for grundvandsstand og vandløbsvandføring.

EU's Vandrammedirektiv og Vandplanerne har sat fokus på konsekvenserne af udnyttelsen af grundvandsreserverne på Sjælland. Vandrammedirektivet stiller krav om god økologisk tilstand i vandløb, men det kan være svært at opnå i områder hvor der indvindes drikkevand, når vandløbene tørrer ud om sommeren. Derfor er der i Vandplanerne forslag om at flytte vandboringer for større millionbeløb for bl.a. at forbedre vandføringen i vandløbene.
Vi fik den ide at ændringer i skovene måske kunne være med til at afhjælpe nogle af problemerne ved at øge vandressourcen. Omtrent en tredjedel af skovarealet på Sjælland er nåleskov, der har en markant højere fordampning og dermed meget lavere nedsivning end løvskov (Boks 1). Forskellen mellem 'løv' og 'nål' er i størrelsesorden 115 mm/år, så hvis alle nåleskove på Sjælland på en gang blev konverteret til løvskove ville man få omkring 40 mill. kubikmeter mere vand at gøre godt med, svarende til 80% af vandforbruget i Hovedstadsområdet (Christiansen og Gundersen, 2011).
Spørgsmålet er dog dels om nåleskovene ligger der, hvor der mangler vand, og dels om det ekstra vand vil bidrage til grundvandsdannelse eller blot løbe ud gennem vandløbene om vinteren uden at forbedre vandføringen om sommeren. For at kunne svare på dette er der brug for detaljerede hydrologiske modeller i 3-D, der kan beregne sæsonvariationen i fordampning, nedsivning, grundvandsstand og vandløbsvandføring i større oplande med forskellig arealanvendelse. Fra Miljøministeriets pulje til 'Ecoinnovation' fik vi tilskud til et projekt 'Mere vand fra skove' til at udvikle og tilpasse modelsystemer til at belyse bl.a. scenarier for forskelligt skovdække og illustrere effekten af konvertering fra 'nål til løv'.

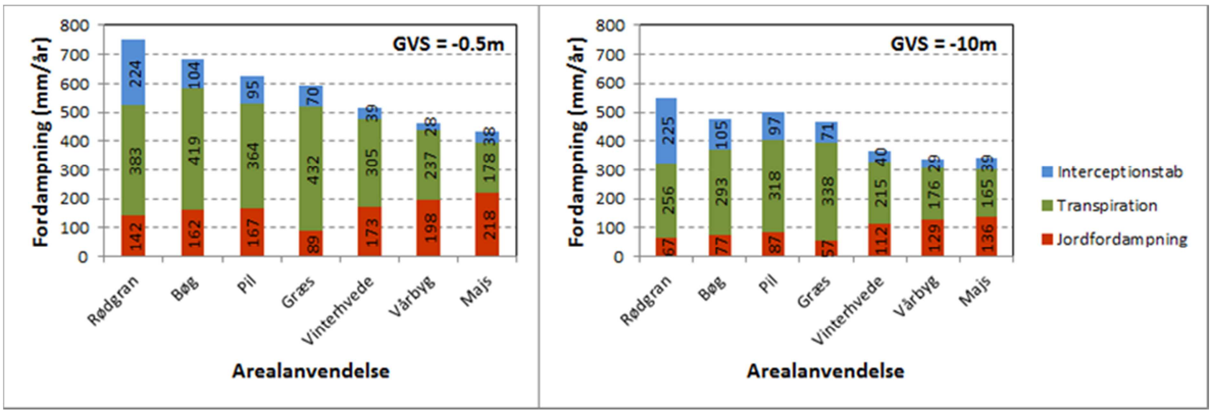
Udvikling af modelværktøj
Hidtil har oplandsmodellerne ikke kunnet beregne fordampningen fra skov tilfredsstillende, især ikke den høje fordampning fra nåleskov (Gundersen m.fl. 2008). Den seneste version af oplandsmodellen MIKE SHE er blevet kombineret med en forbedret fysisk baseret fordampningsmodel (SVAT) (Overgaard, 2005), som vi med tilfredsstillende resultater udviklede og testede for rødgran og bøg (Sonnenborg m.fl. 2014; Bilag 1). Til dette arbejde var det nødvendigt at generere nye grundlæggende parametre for hver skovtype til fordampningsmodulet (SVAT). Vi valgte alene at arbejde med rødgran og bøg, der også er de dominerende træarter i henholdsvis nåleskov og løvskov, selv om andre træarter måske ville give større forskelle i beregningerne (figur 2, boks 1). Til SVAT modelleringen anvendte vi 5-10 år lange dataserier for gennemdryp, jordfugtighed i flere dybder fra to intensive skovovervågningslokaliteter Gludsted (rødgran) og Frederiksborg (bøg) sammen med bl.a. timeværdier for nedbør og andre klimadata. Gennem en række iterative trin (sensitivitetsanalyse, kalibrering og validering) fik vi fastlagt sæt af parameterværdier til beregning af fordampning fra rødgran og bøg. Da parameterværdier for landbrugsafgrøder (græs, vinterhvede, byg og majs) og pil (som eksempel på en flerårig energiafgrøde) var til rådighed fra andre arbejder, kan vi sammenligne resultater for rødgran og bøg med disse afgrøder.

Forskelle i fordampning

En beregning på samme jordbund og med samme klima (3 års klimadata fra Gludsted) illustrerer forskellene i fordampning (grøn) og nedsivning (blå) for hver arealanvendelse/afgrøde (figur 3). I venstre side er vist en beregning med høj grundvandsstand, hvor der således aldrig mangler vand og fordampningen derfor er maksimal, mens der i højre side er vist beregninger med dybt grundvand, hvor fordampning i perioder bliver begrænset af vandmangel i den øverste del af jorden. Ved højt grundvand er fordampningen højest i rødgran, der har 'blade' på hele året, og lavest i majs, der har en ret kort og sen vækstsæson. Nedsivningen fordeler sig omvendt idet den er nedbøren (918 mm/år) minus fordampningen. Med et dybt grundvandspejl udlignes forskellene mellem plantearterne, mens der synes at være en væsentlig forskel mellem vedvarende plantedække (skov, pil og græs) og afgrøder med kortere vækstsæson (hvede, byg og majs). Rødgran har stadig den højeste fordampning på 549 mm/år mod 475 mm/år i bøg, hvilket er en mindre forskel end, der blev fundet i andre studier (figur 1 og 2).



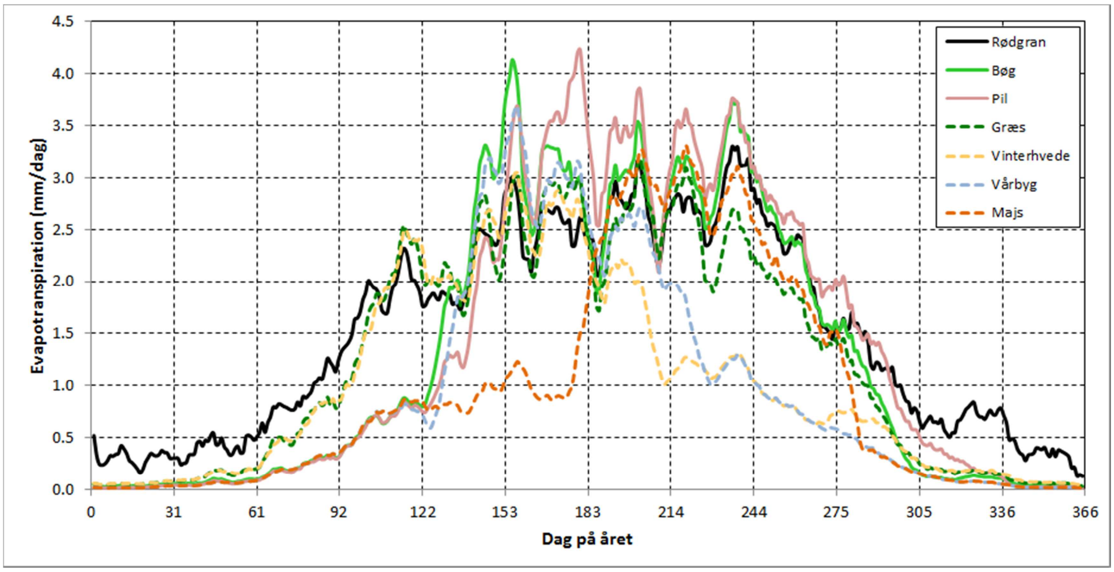
Figur 3: Fordelingen mellem årlig fordampning (grønne søjler) og nedsivning (blå søjler) fra forskellig vegetation beregnet for en 3-årig periode med en gennemsnitlig nedbør på 918 mm/år til venstre for et fugtigt lavbundsområde med højt grundvandsspejl (-0,5 m) og til højre for et højbundsområde med dybt grundvand (-10 m).



Figur 4: Fordampning opdelt på bidrag fra interception, transpiration og jordfordampning for højt og dybt grundvand som i figur 3.

Modellen beregner fordampningen fordelt på tre typer: interceptionstab, transpiration og jordfordampning, se figur 4. Interceptionstabet udgøres af det vand, som bliver hængende på planteoverflader efter en regnbyge og derefter fordamper, dvs. det aldrig når ned til jorden. Dette tab er højest i rødgran (225 mm/år), der både har et stort overfladeareal i kronen og 'beholder nålene på' hele året. Det store interceptionstab i rødgran (og andre nåletræarter) er årsagen til den generelt højere fordampning og lavere nedsivning fra nåletræer end fra løvtræer. Transpirationen (vand der optages gennem rødderne og fordamper ud af bladene) varierer ikke så meget for vegetationstyper med vedvarende plantedække og er lavest for byg og majs med den korteste vækstsæson. Omvendt bliver jordfordampningen størst for afgrøder, hvor der er perioder med bar jord.

Variationen i fordampning hen over året for de seks typer arealanvendelser/afgrøder er vist i figur 5. Her fremgår det, at rødgran har fordampning hele året. Græs og vinterhvede har blade om vinteren og fordampningen øges derfor hurtigt i løbet af foråret, mens den starter senere for bøg, byg og pil, når de har fået blade og sidst for majs, der udvikler sig sent. Når hvede og byg modner (og bliver høstet) i juli/august falder fordampningen herfra, mens de øvrige afgrøder og træer fortsat har høj fordampning. Figuren illustrerer den relativt store forskel der er på fordampningen fra forskellige afgrøder på forskellige tidspunkter af året.

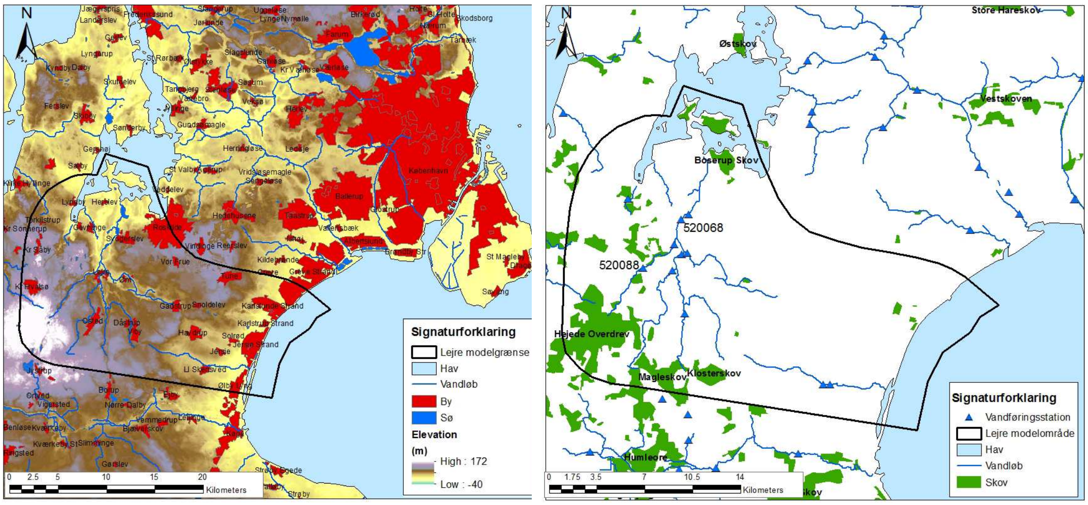


Figur 5: Sæsonvariationen i fordampning fra forskellig vegetation (gennemsnit fra beregning over 3 år) på et højbundsområde med dybt grundvand (-10 m).

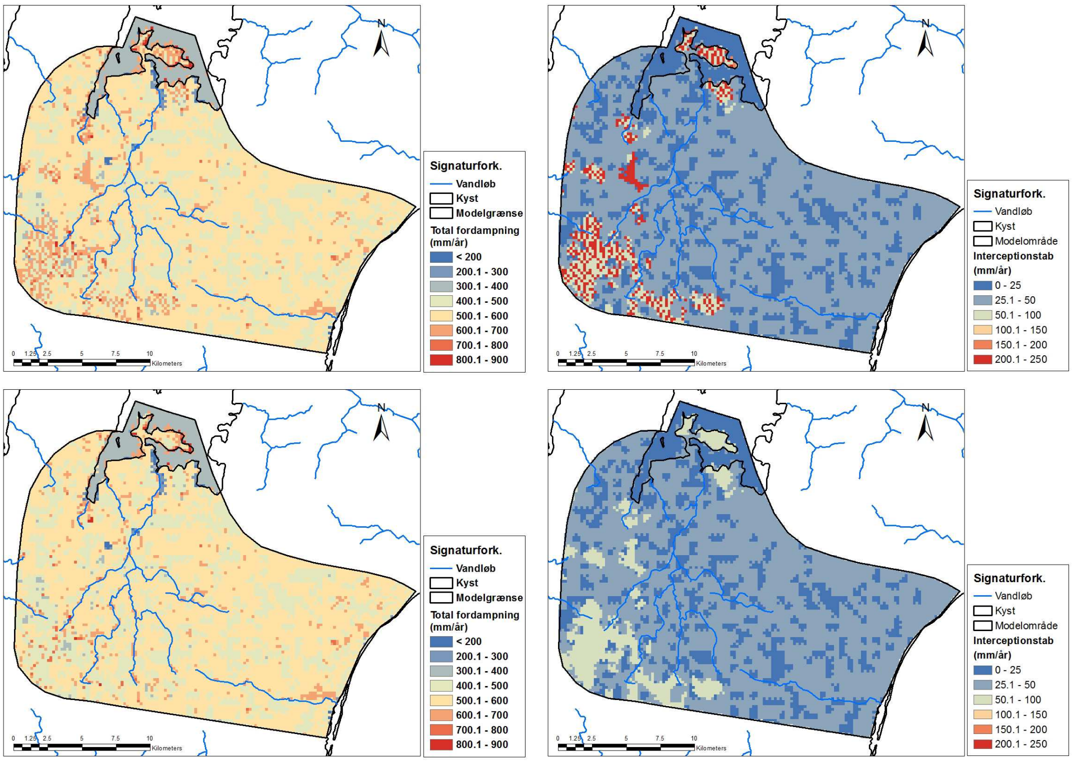
Oplandsmodel, Lejre

SVAT-beregningerne gælder for et punkt og vedrører processerne i rodzonen. For et helt opland skal beregningen af fordampning og nedsivning foretages i hver enhed (pixel) i forhold til den vegetation som findes (eller hvis der arbejdes med scenarier, den vegetation man ønsker). Disse SVAT-beregninger i hver pixel kobles til MIKE SHE modellen, der opsættes således at den beskriver vandbevægelserne i jorden under rodzonen, grundvandsstanden og strømningen i vandløbene. Den samlede MIKE SHE SVAT model kan så for en given længere periode (>10 år) med klimadata kalibreres mod målte data for grundvandstand og vandløbsafstrømning (Bilag 2).

Oplandsmodellen blev sat op for et opland på Midtsjælland, der strækker sig ud mod Køge Bugt, der bl.a. indeholder Langvad Å-systemet (figur 6). Skovene (9,3 % af arealet) ligger især i de højere beliggende dele i den vestlige del af oplandet. Vi havde ikke adgang til digitaliserede kort over fordeling af nål- og løvbevoksninger, men ved en analyse af skovkort fra området blev det konstateret, at skovene består af en mosaik af mindre stykker af de to skovtyper arealmæssigt omtrent ligeligt fordelt. I beregningerne blev 'nål' (47%) og 'løv' (53%) derfor blot tilfældigt fordelt i pixels på skovarealet. Dette fremgår på kortene over fordampning og interception øverst i figur 7, hvor høj fordampning og interception (rød signatur) afspejler nåleskovens placering. En tilsvarende tilfældig placering af forskellige afgrøder på landbrugsarealet giver anledning til variationen i det betydeligt lavere interceptiontab (blå nuancer) i resten af oplandet (figur 7, højre side). Fordampningen er 520 mm/år i gennemsnit over oplandet, mens fordampningen fra nåleskov nærmer sig nedbøren på 800 mm/år (figur 7, øverst venstre). I scenariet hvor 'nål' konverteres til 'løv' (figur 7, nederst) forsvinder de fleste pixels med høj fordampning og skovområderne fremtræder ikke tydeligt, dog afspejler kortet med intereceptionstab stadig (løv)skovenes beliggenhed (lys signatur, 50-100 mm/år).



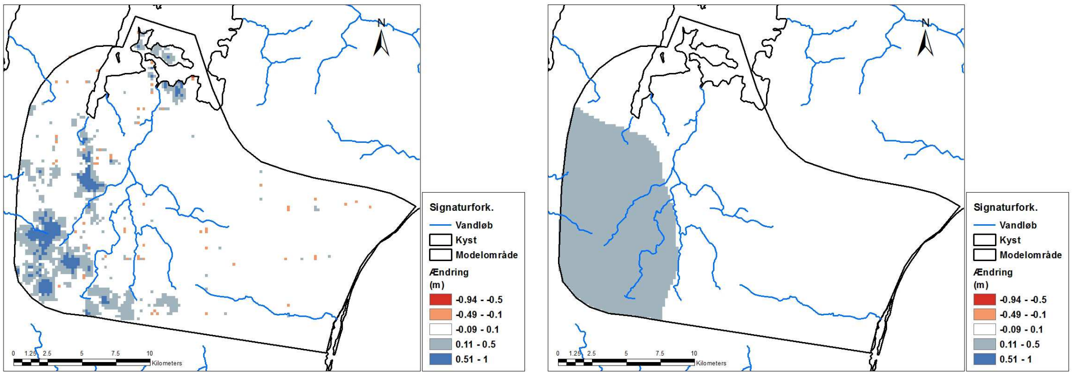
Figur 6: Lejre-oplandet markeret på kort med terrænhøjde til venstre og på kort med skove og vandløb til højre.



Figur 7: Beregnet fordampning (venstre kort) og interceptionstab (højre kort) i Lejre-oplandet, begge i mm/år. Øverst er vist resultaterne for den nuværende arealanvendelse og nederst for et scenarie, hvor nåleskov er konverteret til løvskov. Gennemsnit af 10 års simulering med gennemsnitlig årlig nedbør på 800 mm.

Mere 'løv' mere grundvand

Når 'nål' konverteres til 'løv' og fordampningen falder (figur 7) stiger grundvandsstanden både i det øvre og det primære (dybere) grundvandsmagasin (figur 8) i områder med skov. Stigningen er 0,5-1 m i det øvre grundvand netop på arealer med skov og mere moderat 0.1-0.5 m i det dybe grundvand, men stigningen sker i hele den højere liggende del af oplandet. Det vil sige at selv om Lejre er et lerjordsopland vil mindre nåleskov medføre en større grundvandsdannelse. På grund af den dårlige hydrauliske ledningsevne i lerjord vil vi forvente en forholdsvis større effekt på vandløbsafstrømning end på grundvandsdannelse af vegetationsændringer i Lejre-oplandet. Modelberegninger både for scenariet 'nål' til 'løv' (B1) og andre mere skovrige eller skovfattige (A1) scenarier (tabel 1) viser da også en direkte sammenhæng mellem ændringer i nettonedbøren og afstrømning. Fx ved konvertering af 'nål' til 'løv' (B1) stiger nettonedbøren med 5 mm/år, hvilket medfører en tilsvarende stigning i afstrømningen på 5 mm/år svarende til 3%.



Figur 8: Ændringen i grundvandsstanden i det øvre (til venstre) og det primære (til højre) grundvandsmagasin efter konvertering af 'nål' til 'løv' på skovarealet i Lejre området.

Tabel 1: Ændringer i årlig vandbalance (mm/år) som gennemsnit af 10-års simulering for oplandet til vandføringsstationen 520068 i Langvad Å, Lejre. Absolutte værdier er oplyst for den nuværende arealanvendelse (P1), mens relative ændringer i forhold til P1 er opgivet for de øvrige scenarier. Absolutte ændringer i mm/år står først fulgt af relative ændringer i parenteser. Middelnedbøren er 801 mm/år. Forskellen mellem nettonedbør og afstrømning udgøres af grundvandsudstrømning fra det topografiske opland til st. 520068 samt oppumpning og eksport af vand.

Scenarie	Arealanvendelse	Fordampning	Nettonedbør	Afstrømning
P1	nuværende	520	278	190
B1	'nål' til 'løv'	-5 (-1%)	+5 (+2%)	+5 (+3%)
B2	'løv' x 2	-1 (0%)	+1 (0%)	+1 (+1%)
B3	'løv' overalt	+49 (+9%)	-48 (-17%)	-47 (-25%)
S1	'løv' til 'nål'	+6 (+1%)	-6 (-2%)	-6 (-3%)
S2	'nål' x 2	+17 (+3%)	-17 (-6%)	-15 (-8%)
S3	'nål' overalt	+137 (+26)	-136 (-49%)	-123 (-65%)
W1	pil lavbund, 9,3%	+6 (+1%)	-6 (-2%)	-6 (-3%)
A1	landbrug overalt	-12 (-2%)	+12 (+4%)	+11 (+6%)

Vandføring i vandløbene

For at undersøge effekten på afstrømningen nærmere blev der trukket data ud af modellen for vandløbsafstrømningen i et mindre vandløb, der har sit udspring i den mere skovdominerede del af oplandet (st 520088), og i Langvad Å (st 520068). I tabel 2 er ændringerne i minimumvandføring beregnet for de to stationer som resultat af de forskellige scenarier. Minimumsvandføringen har væsentlig betydning for den økologiske tilstand bl.a. fordi højere minimumsvandføring reducerer risikoen for udtørring. Minimumsvandføringen stiger med 1.2 l/s svarende til 7% i det mindre vandløb ved konvertering af 'nål' til 'løv' (B1, tabel 2) mens det har mindre betydning i Langvad Å, hvor skov kun udgør en lille del af oplandet.

Mere drastiske arealanvendelses ændringer (B3, S3 og A1) har selvsagt store konsekvenser for vandføringen (tabel 2). Modellens beskrivelse af afstrømningen inkluderer dræning (med rør og/eller grøfter) fordi dette er det normale på markerne, der dominerer oplandet. Dette gælder i mindre grad i skov, selv om der kan være grøfter, derfor undervurderer modellen skovarealernes virkninger på vandføringen. Mindre dræneffekt betyder langsommere afgivelse af vandet, så den maksimale vandføring bliver mindre, mens minimumsvandføring øges mere end modellen forudsiger (Sonnenborg m.fl. 2009).

Tabel 2: Ændringer i median-minimumsafstrømningen i et mindre relativt skovdomineret vandløb (st. 520088) og i Langvad Å (st. 520068) ved forskellige arealanvendelsesændringer. Placeringen af stationerne fremgår af figur 6 (højre panel).

Scenarie	Arealanvendelse	Skovdomineret vandløb Median min. (l/s)	Ændring (%)	Langvad Å Median min. (l/s)	Ændring (%)
P1	nuværende	18	-	164	-
B1	'nål' til 'løv'	19	+7	168	+2
B2	'løv' x 2	18	+1	163	-1
B3	'løv' overalt	13	-26	126	-23
S1	'løv' til 'nål'	17	-4	162	-1
S2	'nål' x 2	16	-10	152	-7
S3	'nål' overalt	8	-57	92	-44
W1	pil lavbund, 9,3%	17	-2	163	-1
A1	landbrug overalt	24	+38	177	+8

Sammenligning af arealanvendelser

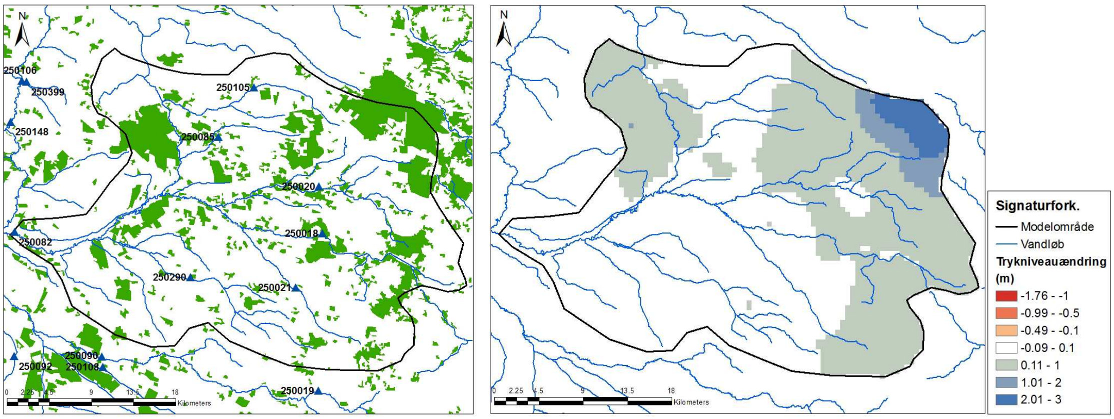
Som det fremgår af tabel 1, blev der gennemregnet flere forskellige scenarier for skovtype, skovareal og energiafgrøder (pil). Fordobling af skovarealet (til 18.6%) udelukkende med bøg (B2) og piledyrkning på våde arealer (W1) så skov og pil tilsammen udgør 18.6% er måske realistiske scenarier for fremtiden, mens fuldstændig dække med bøg (B3), rødgran (S3) eller landbrugsafgrøder (A1) blot er medtaget for at illustrere de store forskelle i vandbalancen (tabel 1) og vandføring (tabel 2) mellem disse anvendelser. Et interessant resultat i forhold til skovrejsning er, at vandbalance og vandføring er uændret ved fordobling af skovarealet (B2), idet øget fordampning fra det større skovareal med bøg bliver kompenseret af reduceret fordampning fordi rødgran samtidig også er erstattet med bøg. Tilsvarende er der også kun en marginal påvirkning af vandbalance og vandføring med pil på våde arealer, formentlig fordi pil erstatter græs eller lign. som har tilsvarende høj fordampning på lavbund, fordi der ikke mangler vand.

Scenarie B3 med fuldstændigt dække med løvskov (bøg), kan ses som en repræsentation af hvordan vandbalancen kan have været før jernalderbønderne fældede skovene på Sjælland. Fordampning har været højere (måske 50 mm højere, tabel 1), men om minimumsvandføringen ville være mindre, som modellen beregner, er nok mere tvivlsomt, idet vi i modellen ikke har kunnet rulle dræning, uddybning og udretning af å'er m.v. tilbage.

Vandbalance på sandjord

MIKE SHE SVAT modellen blev også sat op for en del af Skjern Å-oplandet, som har sandede jorde og bl.a. inkluderer Gludsted Plantage i den højest beliggende del mod øst (figur 10, venstre panel). Modellen blev kørt med tilsvarende beregninger og scenarier som gennemgået ovenfor for Lejre. Selv om nedbøren er højere i Skjern end i Lejre (1063 mod 801 mm/år i simuleringerne), var fordampningen fra oplandet med den nuværende arealanvendelse den samme (520 mm/år), hvilket hænger sammen med at lerjorden i Lejre holder bedre på vandet end sandjorden i Skjern. Så selv om det regner mindre i Lejre, er der ligeså meget vand til rådighed til fordampning i oplandet.

Konvertering af 'nål' til 'løv' i dette opland medførte større påvirkning af grundvandstanden end i Lejre. Figur 10 (højre panel) viser, at grundvandsstanden i det primære grundvandsmagasin stiger med op til 3 meter med bøg i stedet for rødgran (når der har indfundet sig en ligevægt efter ændringen i arealanvendelse). Dette skyldes dels at et større skovareal konverteres og dels at nedbøren (og dermed forøgelsen i nettonedbøren) er højere. Desuden er nedsivningen til grundvandet større i sandjord, hvilket også betyder, at vandføringen fra skovområdet i Skjern som forventet blev væsentligt mindre påvirket end i Lejre.



Figur 9: Den øverste del a Skjern Å oplandet (Ahlergaarde-oplandet) med 17,4 % skov, fortrinsvis 'nål' (venstre panel) og ændringen i grundvandsstand for det primære grundvandsmagasin efter konvertering af denne nåleskov til løvskov (højre panel).

Konklusion (på artikel)

Konvertering af eksisterende 'nål' til 'løv' på lerjord i Lejre-oplandet (og således formentlig også på resten af Sjælland) gav både højere grundvandsdannelse og en forøgelse af minimumsvandføringen i mindre vandløb. Det primære grundvandspejl steg med op til 50 cm over et større område med spredte skove. Hvorvidt den øgede grundvandsressource fra konvertering kan nyttiggøres til drikkevand eller bedre tilstand i vandløbene, kræver en nærmere konkret analyse i forhold til placeringen af boringer m.m. i Lejre-oplandet (og på Sjælland i øvrigt). Med de udviklede modeller er det muligt at vurdere tiltag i skovrige oplande til drikkevandsboringer eller at vurdere den hydrologiske effekt af større skovrejsningsprojekter. Repræsentation af dræning i modellen bør forbedres for bedre at kunne simulere dræningsforholdene i skove.

3. Konklusioner

'Mere vand fra skove' har som helhed opfyldt de mål, der var udstukket for projektet (side 10). De følgende konklusioner vedrører ikke alene problemstillingen i det foregående kapitel, men også de arbejder, der er beskrevet i de to efterfølgende mere tekniske bilag.

- Arbejdet med fordampningsmodellering viste, at både løvskov (bøg) og nåleskov (rødgran) kan parameteriseres tilfredsstillende i SVAT-modulet til MIKE SHE, når der arbejdes med timeværdier for nedbør (Bilag 1). Timeværdier er nødvendige for at kunne beskrive interceptionsfordampning korrekt, da interceptionsmagasinet tømmes på langt mindre end et døgn. Det er således muligt at sammenligne vandbalanceberegninger for de to skovtyper med beregninger for landbrugsafgrøder (græs, vinterhvede, byg og majs) og energiafgrøder (pil) i samme energi-baserede model koncept. Dette selv om SVAT-modulet ikke inkluderer sne og snesmeltning, men alene behandler nedbør som regn.

- Fordampningen fra de forskellige vegetationstyper varierer over året og er styret af udspring, vækstperiode og bladareal. Interceptionstabet i rødgran (og andre nåletræer) er af særlig betydning for vandbalancen og giver anledning til en betydelig fordampning i vintersæsonen, hvor fordampningen er minimal fra både bøg og landbrugsafgrøder.

- Baseret på MIKE SHE SVAT er der udviklet opsætninger for to oplande (Skjern og Lejre) på henholdsvis sand- og lerjorde (Bilag 2). Modellen er avanceret og beskriver vandstrømme i jord og grundvand i 3D. Arealanvendelsen er distribueret på overfladen; det har således betydning for resultaterne, hvor der er skov i forhold til hvor der er landbrug. Modellen giver mulighed for analyse af hydrologiske aspekter af potentielle scenarier for arealanvendelse fx skovrejsning, energiafgrøder m.m. Udfordringen med dette modelværktøj på oplandsskala er, at det er data- og beregningstungt, og kræver speciel viden om undergrunden, samt opsætning og kalibrering af 3D modellen for hvert opland. Yderligere udvikling af parameterisering af modellen er nødvendig for at lette anvendelse i nye oplande.

- For at opbygge scenarier for arealanvendelse og placering af nye arealer med skov eller energiafgrøder i et opland efter objektive kriterier blev der udviklet et GIS-hjælpeværktøj i et tilknyttet projekt. I scenarier for skovrejsning blev den nye skov fx placeret i de mest tørre område med dybt grundvand, mens energiafgrøder blev placeret i områder med højt grundvand.

- På Statens arealer og i nogle private skove er den langsigtede målsætningen at konvertere nåleskov til løvskov. Det er derfor centralt at kunne forudsige konsekvenserne for vandkredsløbet af disse ændringer i skovene og evt. at udnytte konvertering som et aktivt virkemiddel til at få mere vand i landskabet. Konvertering på lerjord i Lejre-oplandet (og således formentlig også på resten af Sjælland) gav både højere grundvandsdannelse og en forøgelse af minimums-afstrømningen i mindre vandløb. Det primære grundvandspejl steg med op til 50 cm over et større område med spredte skove. Hvorvidt den øgede grundvandsressource fra konvertering kan nyttiggøres til drikkevand eller bedre tilstand i vandløbene, kræver en nærmere konkret analyse i forhold til placeringen af drikkevandsboringer m.m. i Lejre-oplandet (og på Sjælland i øvrigt). I det sandede Skjern-opland gav konvertering en større forøgelse af grundvandsstanden (op til 3 m), men kun en marginal ændring af vandløbsvandføringen.

- Gennemregning af scenarier for skovrejsning i de to oplande viste, at en fordobling af skovarealet med løvskov vil reducere nettonedbøren, hvilket dog på oplandsniveau kunne modvirkes af en vis konvertering af 'nål' til 'løv' i den eksisterende skov. Plantning af pil som energiafgrøde (med samme arealmæssige omfang som skovrejsning) på jorde med høj grundvansstand (dvs. fortrinsvis på vandløbsnære arealer) gav øget fordampning, men kun marginale ændringer i minimumsvandføringen (Bilag 2).

- Gennemregning af ekstreme scenarier med henholdsvis landbrug, løvskov eller nåleskov på hele arealet i de to oplande viste, at arealanvendelsen har stor indflydelse på vandbalance og vandløbsvandføring (Bilag 2). Dette illustrerer behovet for at hydrologiske modeller har en god beskrivelse af fordampning fra de forskellige vegetationstyper. Scenariet med fuldstændigt dække med løvskov, der kan ses som en repræsentation af hvordan vandbalancen kan have været i forhistorisk tid før bønderne fældede skovene, viste at fordampningen alt andet lige (fx samme klima og samme dræning som nu) har været højere (måske 50 mm højere) og vandføringen derfor mindre dengang landet var skovdækket.

- Sammenligning af vandbalancer på forskellig jordbund er vanskelig i Danmark, idet de sandede oplande i vest ofte har højere nedbør end de lerede i øst. Dette gælder også Skjern og Lejre, hvor nedbøren var henholdsvis 1063 mod 801 mm/år. Overraskende nok var fordampningen den samme (520 mm/år) fra de to oplande med den nuværende arealanvendelse, hvilket hænger sammen med at lerjorden i Lejre holder bedre på vandet end sandjorden i Skjern. Så selv om der kommer mindre vand med nedbøren i Lejre, er der ligeså meget til rådighed til fordampning. Som forventet var der relativt mere grundvansdannelse i det sandede end i det lerede opland, hvilket afspejler den høje og lave hydraulisk ledningsevne i henholdsvis sand- og lerjorde.

- Beregningerne er behæftede med en række kilder til usikkerhed. Dette gælder fx simplificering af beskrivelsen af de forskellig vegetationers udvikling i bladareal over året eller af vandløbenes placering i de forskellige pixels i modellen. Den største usikkerhed i forhold til vandløbsvandføring er dog beskrivelsen af dræning i modellen. Denne er beskrevet i forhold til den dominerende landbrugsanvendelse, hvor der sædvanligvis er et system af drænrør og grøfter til at sikre effektiv afvanding. Desuden er modellens 3D-beskrivelse af processer i jord og grundvand kaliberet til den aktuelle arealanvendelse, hvorfor beregningerne af scenarier med ændret vegetation på overfladen ikke kan inddrage evt. følgeændringer i de dybere lag i modellen. Der tages således ikke højde for, at dræningen er mere begrænset i skov og at træernes rødder efter skovrejsning vil gro ind i drænsystemerne og gradvist reducere deres effektivitet. En bedre beskrivelse af dræning og gennemregning af forskellige scenarier for dræningseffektivitet bør være et fokuspunkt i det videre arbejde med oplandsmodeller. Dette er nødvendigt for at få mere realistiske resulter for vandføring i vandløb i skovrige dele af et opland eller for scenarier med skovrejsning. Vi vurderer at den nuværende model underestimerer den positive effekt af skov og skovrejsning på minimumsvandføring idet vandets opholdstid på skovarealerne bliver for kort på grund af effektiv dræning i modellen i forhold til den reelle mindre dræning i skovene.

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Bilag

1. Sonnenborg *et al.* 2014a. Modeling of canopy interception, throughfall and groundwater recharge in Norway spruce, beech and agricultural crops (draft for submission to a peer-review journal)

2. Sonnenborg *et al.* 2014b. Modeling of afforestation in a sandy and a clayey catchment: impact of forest type and coverage on groundwater resources (draft for submission to a peer-review journal)

Bilag 1:

Modeling of canopy interception, throughfall and groundwater recharge in Norway spruce, beech and agricultural crops

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Content

Abstract

In this study, the water balance of forest (beech and spruce), willow SRC, and agricultural crops (grass, corn, wheat and barley) have been estimated using the physical based hydrological model MIKE SHE SVAT. Based on measurements of throughfall, energy flux and soil water content from a field station located in the Gludsted conifer forest (Western part of Denmark), the energy based SVAT model has been calibrated yielding vegetation parameters for spruce. The same method has been used to estimate broadleaf forest parameters, using data from a beech forest in Frederiksborg (Eastern part of Denmark). Parameters from Mollerup (2011) have been used for agricultural crops while literature parameters values for willow have been used. All these parameterizations have been used in a one-dimensional vertical representation of the site using climate data from Gludsted, to quantify the differences in water balance and groundwater recharge for different depths to the groundwater table. Total evapotranspiration (ET) together with its components, i.e., transpiration, soil evaporation, and evaporation from interception are presented. The SVAT model is found to yield an acceptable representation of the processes dominating evapotranspiration from forest (both conifer and broadleaf) if input data and model time steps with a resolution of hours is used. Based on the model formulation and the available observation data it was possible to estimate physically reasonable vegetation parameters that resulted in acceptable validation tests. Water balances at plot scale indicate that higher evapotranspiration can be expected from spruce compared to beech which again is higher than for crops. The differences depend on water availability (groundwater depth). Differences in total annual ET between spruce and maize are estimated to 325 mm/yr and 210 mm/yr for groundwater depths of 10 m and 0.5 m, respectively. Hence, the impact of vegetation type on groundwater recharge is potentially significant.

1 Introduction

Land-use is an important factor influencing the catchment water balance and changes in land-use is an on-going process in many countries. In Denmark, different studies of water fluxes of different tree species generally agree that deciduous forest yield more water than coniferous forest. Christiansen et al. (2006) compared the fluxes from beech and Norway spruce located on the same soil type, by using the process oriented CoupModel. They revealed that the differences in interception loss account for the differences in percolation between beech and Norway spruce. The interception loss from the beech stand was only 18% of precipitation, while it was as much as 46% from the Norway spruce stand. Other deciduous species, including ash, beech, oak, lime and maple were modeled and compared by Christiansen et al. (2010). They found that maple has the highest throughfall and percolation, followed by lime, oak and beech. All the deciduous species were found to yield higher throughfall and percolation than Norway spruce. Similarly, Salazar et al. (2013) used the DAISY model to compare water balances in oak and Norway spruce grown on former farmland. They found declines in water recharge after afforestation, which was mainly due to the increase in interception loss. The comparison between oak and Norway spruce revealed that oak produce higher groundwater recharge than Norway spruce. In low precipitation years Norway spruce produced no recharge whereas oak always did.

Hence, canopy interception of precipitation is a key factor in the forest water balance as it controls both direct evaporation of precipitation, the input of water to the soil and hence percolation of water through the soil (Christiansen et al. 2006; Ladekarl et al. 2005; Mossin and Ladekarl 2004; van der Salm et al. 2006; Rosenqvist et al. 2010). Interception storage and evaporation is related to tree species dependent canopy characteristics. Leaf area magnitude and dynamics are important as the amount of water than can be intercepted is proportional to the leaf surface of the canopy. However, leaf surface properties, such as roughness, determine whether water drops stay on the leaf or are transported of the leaf quickly. Also, species dependent canopy structure, e.g. layered or not, is important. For example, it was shown recently that adjacent, evenly aged maple and beech stands with the same leaf area index (LAI) had widely different precipitation interception (Christiansen et al. 2010). This difference in interception was attributed partly to differences in leaf surface roughness, e.g. maple being less rough and thus easing water runoff from leaf surface, and partly to the fact that maple trees tend to form a shallow canopy depth contrary to the beech trees that form a multi-layered canopy.

Direct measurement of interception evaporation is unfortunately not possible with current techniques. Using, e.g. eddy covariance, the water flux measured from the vegetation by an eddy tower integrates all sources of evaporation, including contributions from the soil surface, transpiration and direct evaporation of water drops from leaf surfaces. An indirect measure of the interception loss is obtained by measuring the canopy throughfall (TF) water flux which will be reduced compared to bulk precipitation above the canopy. Alternatively, empirical and process based modeling, e.g. by soil-vegetation-atmosphere-transfer models (SVAT), of the forest water balance has been used as a tool to assess both tree species effects (Christiansen et al. 2006, 2010) and the impact of afforestation (van der Salm et al. 2006; Rosenqvist et al. 2010) on the water balance at stand level.

With the implementation of the ambitious afforestation plan and the need for renewable energy sources, the structure and type of forest and coverage are changing in Denmark. It is therefore necessary to study the hydrological implications of the possible land-use changes. Recently, a SVAT code was integrated into the MIKE SHE catchment modeling framework (Overgaard, 2005) making it possible to differentiate soil evaporation, transpiration and canopy interception loss contributions. By studying and understanding the potential response to the land-use change, it would offer a guideline for researchers and policy makers to better understand the relationship between land-use and water balance, and hence better protect the environment.

Using the SVAT implementation in MIKE SHE (Overgaard, 2005), our primary objectives were 1) to test the performance of throughfall modeling with long term series of measured canopy throughfall for two contrasting forest types (one conifer and one broadleaf) in Denmark, 2) to compare modeling results where calibration is based on throughfall data only with results from modeling where data on both throughfall, soil water content and energy flux are utilized, and 3) to present representative parameter sets for different common forest types in Denmark (to be used subsequently in large scale modeling of land-use change effects on water resources), and 4) to evaluate the impact of land use on plot scale water balances.

The article is organized in three sections. 1) In the first part materials and methods are described including the study sites, (e.g., soil and climate characteristics) together with the model used. The controlling parameters are described and inputs are compared with long term trends. 2) Water balances for each vegetation type are presented. 3) Results are compared with other available studies. Finally, the parameters used are discussed together with the limitations of the model.

2. Materials and methods

MIKE SHE SVAT models for different land-use types were built up using meteorological observations (precipitation, air temperature, wind speed, etc.) from two forest locations, together with available observations of fluxes and state variables. Long term monitoring of Danish forest ecosystems have supplied high quality data of water fluxes for a wide range of forest types in Denmark. Two different forest types have been selected (Gundersen et al. 2009): a Norway spruce (coniferous) and a European beech (broadleaf) stand, respectively, in order to study the differences between coniferous and broadleaf on water resources.

2.1 Sites

The conifer forest is located at the Gludsted Plantage, (UTM coordinates E 520792 N 6214432) (Figure 2.1). The Gludsted plantation is located on a plateau near the Jutland ridge at an elevation of 85 m. The soil at the Gludsted site is dominated by coarse grained materials. Both the A, B and C horizons, representing depth intervals of 0 – 0.3 m; 0.3 – 0.8 m and above 0.8 m, have been characterized as loamy sand (Greve et al., 2007). The forest is dominated by 15 to 20 m tall Norway spruce of varying stand age (Ringgaard et al., 2011). The broadleaf forest is located at Frederiksborg, in the northern part of Zealand in the eastern part of Denmark (UTM32 coordinates E 709413 N 6206401), see Fig. 2.1. The elevation is 35 m and the topsoils in the area are characterized as silty soils and are hence more clayey than at Gludsted. The beech stand used at Frederiksborg was planted in 1965 and thus 36 years old for the earliest measurements used. The tree height was 17-18 m and the stand has been managed with regular thinnings. The groundwater table at the two sites was estimated at 10m and 2m below soil surface, respectively, for Gludsted and Frederiksborg and used as boundary condition for the models.

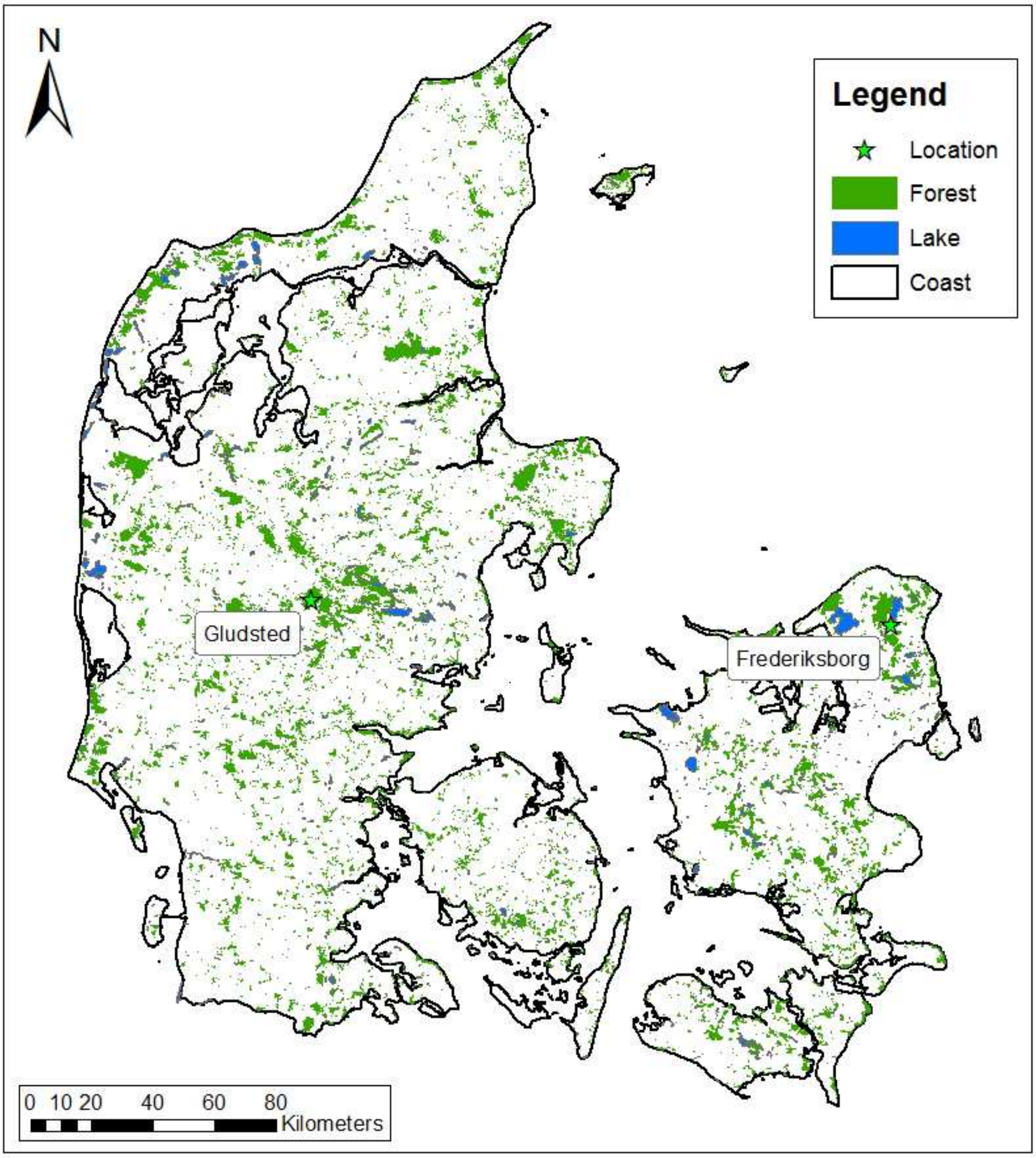

Figure 2.1 Map showing the Skjern Catchment and the location of the Gludsted and the Frederiksborg field stations

2.2 Climate data

Two sources of meteorological data have been used as input to the model at Gludsted. Before 2008 data from DMI were available. Since 2008 data from a field station established by the HOBE project (Jensen and Illangasekare, 2011) are available from the Gludsted plantation (Ringgaard et al., 2011). All the meteorological inputs (precipitation rate, air temperature, etc.) were available at an hourly time step. At Frederiksborg data provided by DMI which have been measured at a nearby climate station in Hillerød were used.

In Fig. 2.2 mean monthly air temperature and precipitation at Frederiksborg during the period from 2001 to 2009 and at Gludsted during the period from 2001 to 2010 are shown. The mean annual air temperature was approximately 8 °C with relatively low inter-annual variations. The precipitation at both stations show relatively higher inter-annual variations than air temperature. At Frederiksborg, mean annual precipitation was around 870 mm. The year 2007 had the highest precipitation of 1173 mm. The year 2001 had the lowest precipitation that amounted to 678 mm. At Gludsted, the mean annual precipitation was in the order of 970 mm. The year 2002 had the highest precipitation which amounts to 1140 mm.

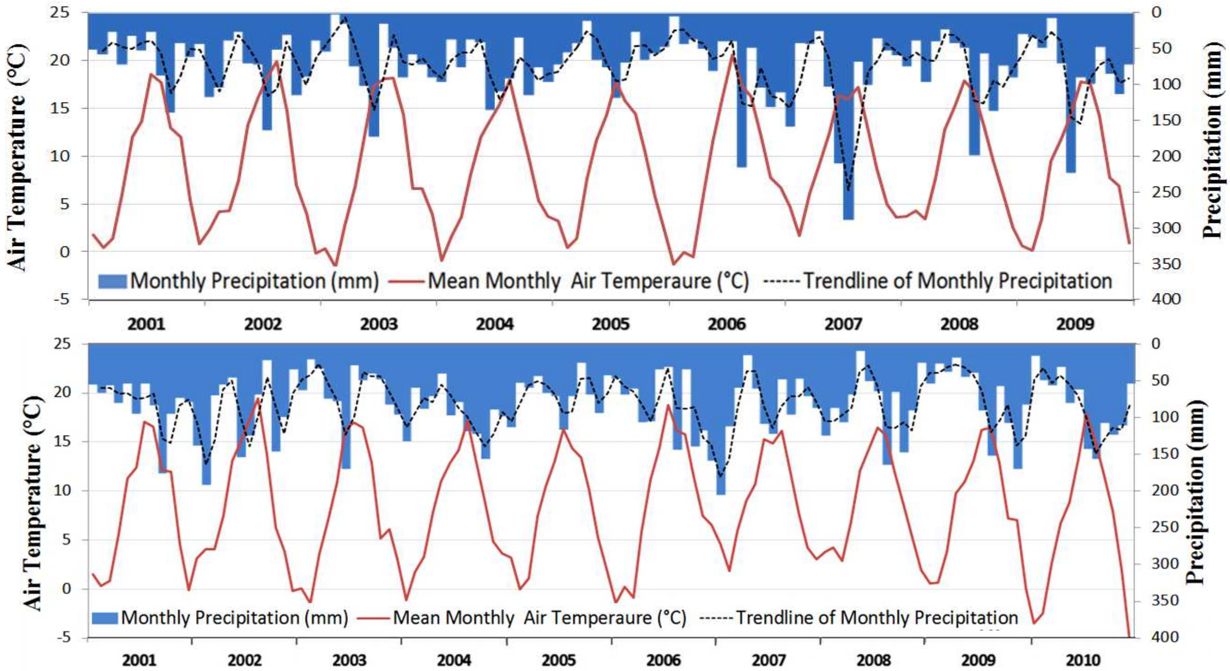

Figure 2.2 Time series of monthly air temperature and precipitation at Frederiksborg in 2001-2009 (top panel) and at Gludsted in 2001-2010 (bottom panel). The monthly values were synthesized from hourly data used in the column model.

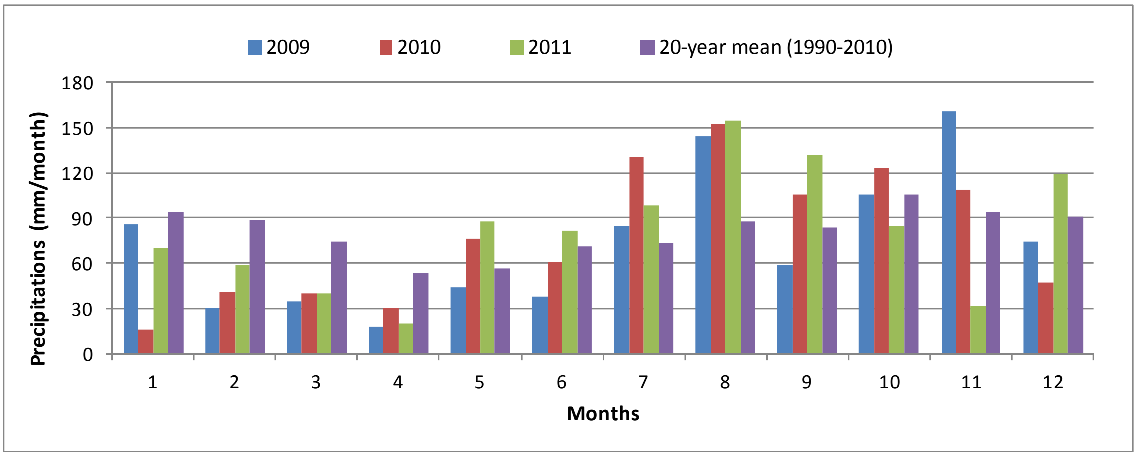

Figure 2.3 Monthly precipitations for the three years used for simulations compared to the 20-year mean precipitations at Gludsted field station

Annual precipitations at Gludsted during 2009-2011 varied from 878 mm/yr to 979 mm/yr with monthly variations shown in Figure 2.3. Difference in term of annual precipitation between 2009 and 2011 equals 101 mm. The annual precipitation of 2011 is very close to the 20-year mean annual precipitation of 972 mm/yr. Therefore, this year is the most representative of the current climate. Overall, precipitation of the three years is higher than average during summer and lower during winter. If we compare the seasonal dynamics of the three years, highest precipitation occurred between July and November.

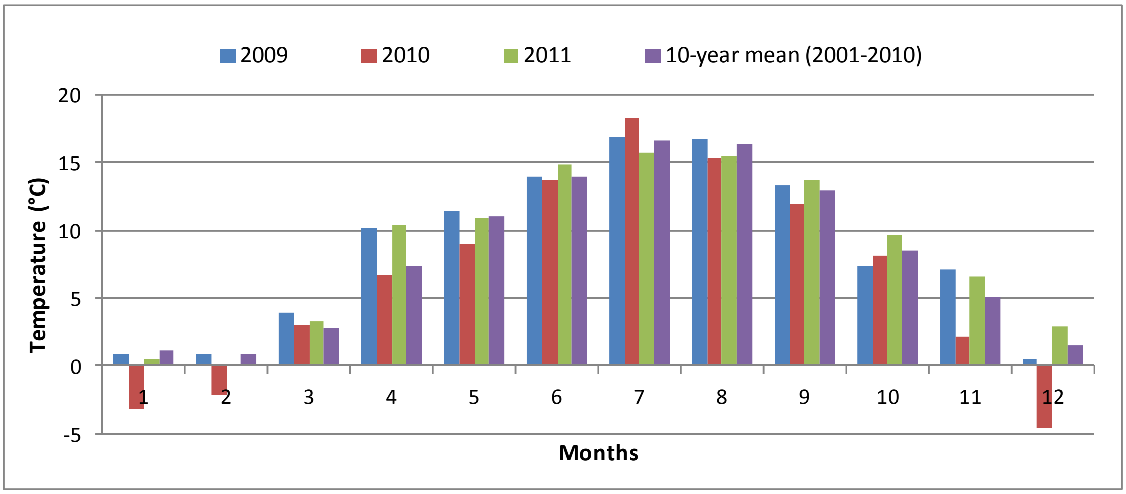

Figure 2.4 Monthly temperatures for the three years used for simulation compared to the 10-year mean temperature at Gludsted field station

Monthly temperatures for the tree years are quite similar during the growing season (April to October) and they follow the trend of the 10-year mean temperature (Figure 2.4). Air temperature in June, July and August was the highest, while in December, January and February it was the lowest. In 2010, higher seasonal variations have been observed with a cooler winter and a warmer middle summer.

2.3 Hydrological data

At Gludsted, energy flux and soil water content have been observed since 2009 by the HOBE project. The energy fluxes were measured by an eddy covariance station (Ringgaard et al., 2011) while soil water content was measured at several depths using TDR equipment. At the Frederiksborg site water content (using TDR) but no energy fluxes have been measured. Measurements of canopy throughfall (TF) are available at both locations. At Gludsted data are available in the period 2001-2006 while data have been collected in the period 2002-2009 at Frederiksborg. The canopy TF was measured with 8 to 10 funnels at each site and averaged data were used to obtain a representative measure of the TF flux at stand level, see Fig. 2.5 and 2.6.

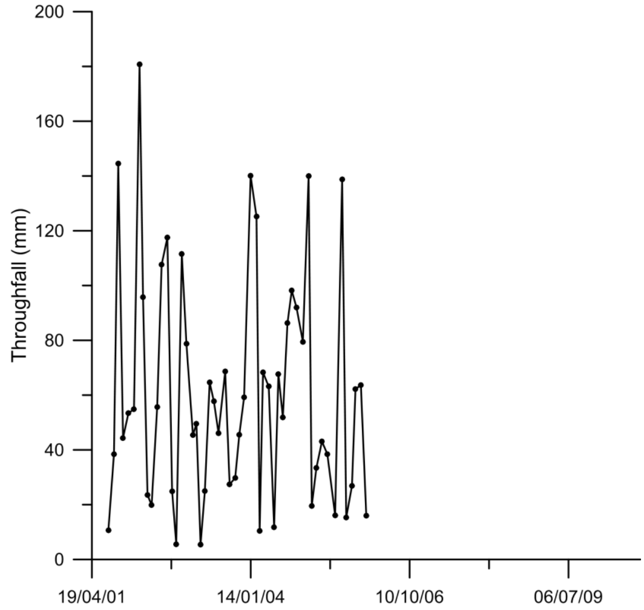

Figure 2.5 Canopy throughfall measured at Gludsted from May 2001 to October 2006. Each point represents the accumulated amount of throughfall between sampling dates.

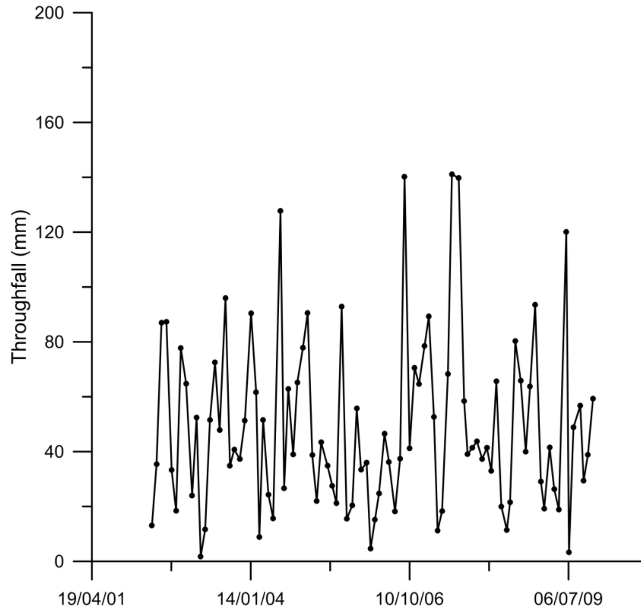

Figure 2.6 Canopy throughfall (mm) measured at Frederiksborg from May 2002 to December 2009. Each point represents the accumulated amount of throughfall between sampling dates.

2.4 MIKE SHE SVAT

The MIKE SHE SVAT model was adopted to simulate water balances in this study. It explicitly describes the water and energy balances between the soil, vegetation and atmosphere by coupling the hydrological processes of the sub-surface, the surface and the atmosphere (Overgaard, 2005). The SVAT model is based on the MIKE SHE model (Abbott et al., 1986; Graham and Butts, 2005), and replaces the simplified evapotranspiration (ET) module (based on potential ET) with a Soil-Vegetation-Atmosphere Transfer (SVAT) module. The SVAT model has been proven satisfactory in several studies;

however, it unavoidably has some limitations: it has notably higher complexity compared to the standard ET model, which causes higher simulation uncertainty (Stisen et al., 2011a) and it does not theoretically model snow cover or dew formation (Lerer, 2011).

In this study three modules of MIKE SHE are used: Evapotranspiration (SVAT), Unsaturated Flow (1D Richards' equation) and Saturated Flow (Darcy flow), where the saturated zone only is used to establish a lower boundary condition for the simulations. The SVAT module is based on the model concept presented by Shuttleworth and Wallace (1985), an energy-based land surface model. It consists of a two layers system comprising the soil and the vegetation canopy. The two-layer system model simulates a single, semi-transparent canopy layer located above the substrate such that the only way for heat and moisture to enter or leave the substrate layer is through the canopy layer. The fluxes of heat and water are driven by differences in temperature and humidity, respectively, and controlled by a number of resistances (Overgaard, 2005). At each time step of the model simulation, the SVAT model is fed with data on precipitation, net or global radiation, humidity, atmospheric pressure, temperature, and wind speed. Meanwhile, the SVAT produces output on latent heat flux and sensible heat flux. The modeling approach can be described by analogy to an electrical resistance system (Figure 2.7).

Figure 2.7 illustrates a leaf (green box) and water on soil and leaf surfaces (blue lines). Temperature and humidity at the wet (w) and dry (d) surfaces (l: leaf surface, s: soil surface, c: mean canopy level) are denoted T and e. The transport of latent heat (LE) and sensible heat (H) is illustrated on the left- and right-hand side of the figure, respectively. Rn is net radiation, and SH is soil heat flux (Overgaard, 2005).

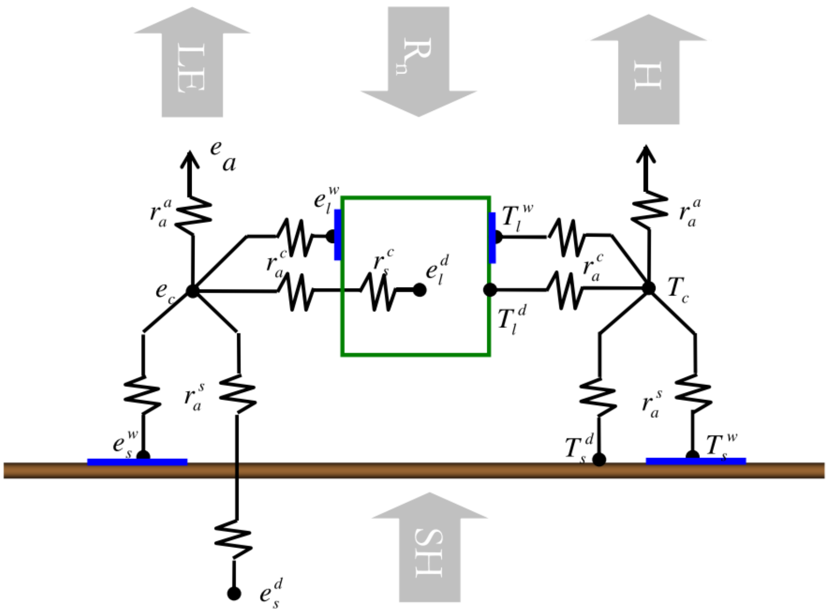

Figure 2.7 Structure of SVAT model described by analogy with an electrical resistance system. See text for explanaition

The resistances are denoted r and control the flux of energy and vapor. The aerodynamic resistance, r_a^a, controls all fluxes. In addition, transpiration (E_t) from the canopy is controlled by the stomata resistance, r_s^c, and the leaf boundary layer resistance, r_a^c.

Interception loss, E_i, is controlled by the leaf boundary layer resistance, r_a^c. Soil evaporation, E_s, is a function of the soil evaporation resistance, r_g (not shown on Fig. 2.7), which increases as the top soil dries out, and the soil surface – canopy resistance, r_a^s. Finally, evaporation from wet soils is a function of the soil surface – canopy resistance, r_a^s.

2.4.1 Model parameters

Soil and vegetation parameters required by the SVAT module include (excluding soil hydraulic properties): leaf area index (LAI), interception coefficient (C_{int}), minimum stomata resistance (RSC_{min}), extinction coefficient (K_{ext}), average leaf width (w), vegetation height (h_{veg}), soil surface roughness (z_{0s}), albedo (α), root depth (z_{rd}), and root mass distribution (A_{root}). Albedo describes the fraction of incoming short wave energy (global radiation) that is reflected to the atmosphere. Hence, the albedo controls the energy available for evapotranspiration where higher albedo means that less energy is available for evapotranspiration.

The leaf area index (LAI) is defined as the total leaf area per unit ground surface area (m^2/m^2). LAI is a key parameter for estimating evapotranspiration, as it directly influences both the evaporation and transpiration of the canopy. The interception coefficient (C_{int}) defines the interception storage capacity of the vegetation per unit of leaf area (mm/LAI). In the SVAT model, the interception storage is calculated for each time step. LAI ad C_{int} directly controls the amount of water stored on leaf surface and thus also the amount transported from the leaf to the ground (throughfall, TF).

The vegetation height (h_{veg}) affects the canopy roughness length and hence the aerodynamic resistance. The aerodynamic resistance decreases with increasing vegetation height. Leaf width (w) affects the leaf boundary layer resistance (r_a^c) and thus the evaporation of intercepted water. Increasing leaf width results in an increase in r_a^c and in a decrease in evaporation of intercepted water. More water will therefore be available to the soil, as TF flux. The minimum stomata resistance (RSC_{min}) is the stomata resistance of leaves in an unstressed condition. Depending on vegetation type, RSC_{min} is normally in the range of 80 - 250 s/m. The actual surface resistance of the canopy is parameterized using a Jarvis-type model (Jarvis, 1976):

$$r_s^c = \frac{\mathrm{RSC_{min}}}{\mathrm{LAI} \cdot \mathrm{F_1} \cdot \mathrm{F_2} \cdot \mathrm{F_3} \cdot \mathrm{F_4}} \qquad (2.1)$$

where the reduction functions F_1 - F_4 represent the influence of radiation, temperature, air humidity and soil moisture on the stomata resistance, respectively (Kelliher et al., 1995).

The extinction coefficient (K_{ext}) describes how much radiation is absorbed by the leaves, and it depends on the angular distribution of leaves. A higher K_{ext} value allows more radiation to reach the soil surface which will result in higher soil water evaporation. However, according to the sensitivity analysis by Bruge (2013), the total evapotranspiration is barely influenced by the value of K_{ext}, due to the offset between different ET components. Normally, K_{ext} varies between 0.3 and 0.7 (Rosenberg et al., 1983).

The soil surface roughness length (z_{0s}) is the height of the substrate air layer in which wind speed equals to zero (Lerer, 2011). Values of 0.025 - 0.03 m are normally used in a SVAT model and the value of z_{0s} is used to calculate the resistance between the soil surface and the canopy air, r_a^s (Overgaard, 2005). Therefore, it can have an impact on the soil evaporation and on the evaporation from ponded water. A sensitivity analysis has shown that an increase of z_{0s} from 0.025 m to 1 m resulted in a relatively small decrease in soil evaporation of 2.5% (for a vegetation height of max. 4 m). Hence, the impact of changing the value of this parameter is relatively insignificant. The root mass distribution (A_{root}) represents the distribution of water extraction with root depth (DHI, 2012). The value of A_{root} depends on soil bulk density and vegetation species. A higher A_{root} value results in higher root mass and corresponding water extraction at shallow soils.

2.5 Parameterization of temporal variations

The actual value of many of the vegetation parameters of the SVAT model is not known a priori. However, the temporal development in LAI and vegetation height were prescribed as known. In Fig. 2.8 the assumed annual variation of LAI and vegetation height is shown for spruce, beech and willow. Vegetation heights for spruce and beech have been specified to a constant value of 17.5 m. For willow, the vegetation is assumed to grow in three year cycles where they are cut at the end of the cycle. The height of the vegetation is assumed to increase steadily from 1 m to 4 m during the period. LAI is specified as constant for spruce. The beech is assumed to come into leaf at May 1 and the maximum LAI is reached within a month. The LAI decrease moderately from beginning of September and the LAI reach its minimum level at the end of October. The willow is assumed to come into leaf in the beginning of April and to reach a minimum LAI at the end of November. The maximum level of LAI increases during the three year growing cycle from 4 to 6.

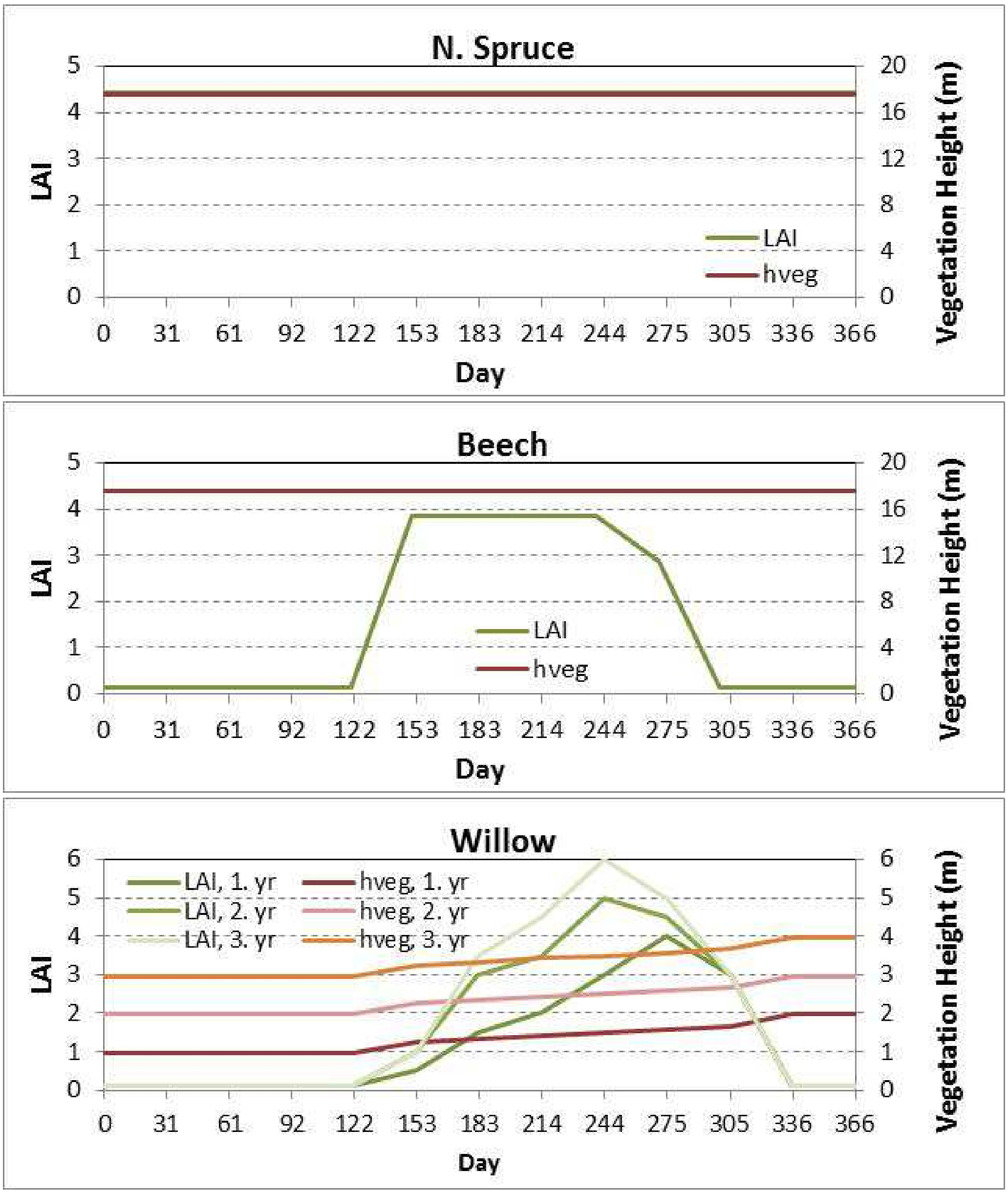

Figure 2.8 Temporal development in leaf area index (LAI) and vegetation height for spruce, beech and willow.

Similar curves for the development in LAI and vegetation height used for the agricultural crops are illustrated in Fig. 2.9. Grass has a relatively low vegetation height and LAI all through the year whereas spring barley and maize only are active during summer. Spring barley has a relatively short growing season, from beginning of May to beginning of August, while the growing season of maize is relatively late, from end of June to harvest in beginning of October. The fields where spring barley and maize are grown are assumed to be without crops between harvest and spring. This period is represented by small values of LAI and vegetation height corresponding to a litter layer or low vegetation.

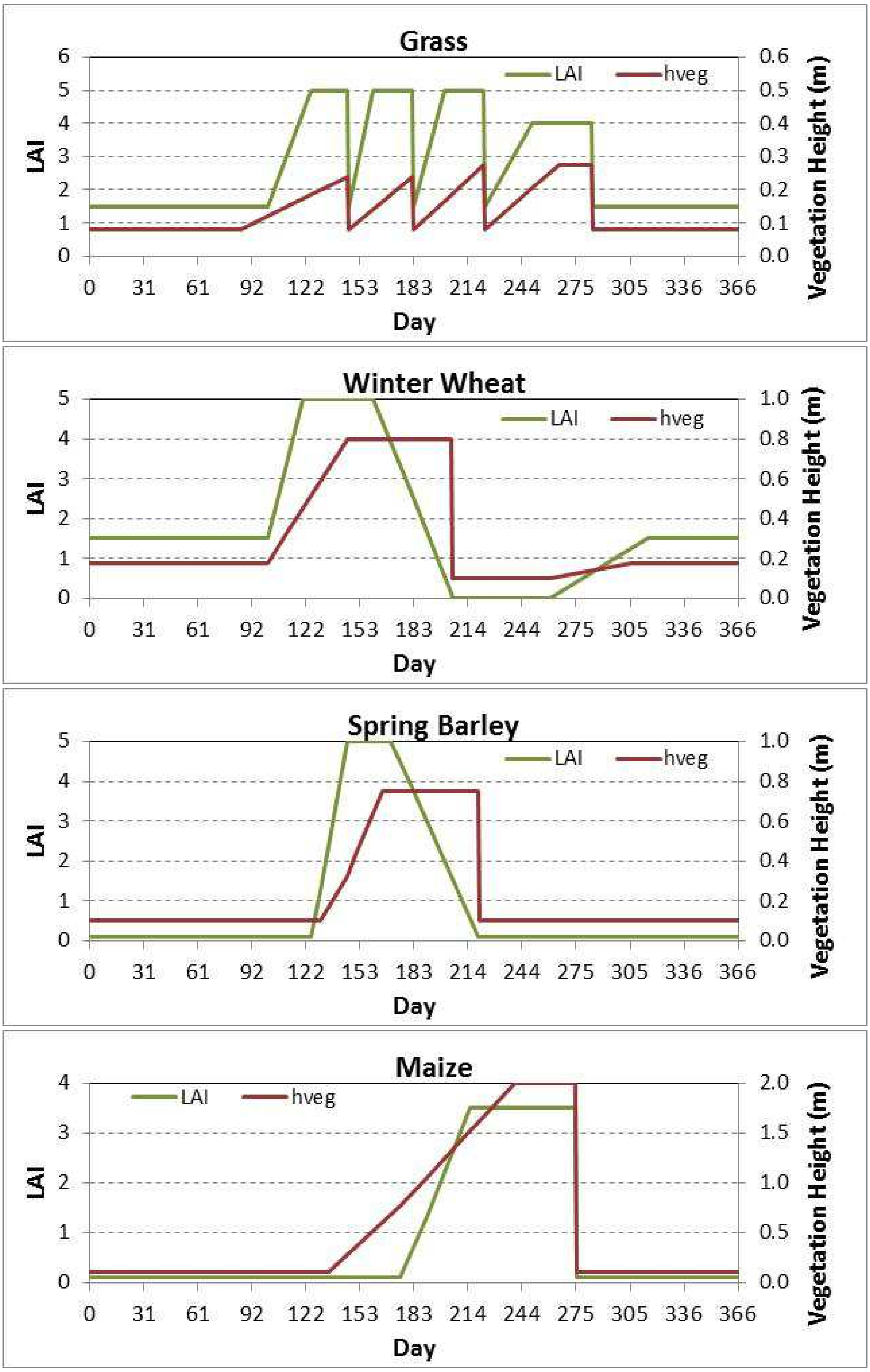

Figure 2.9 Temporal development in leaf area index (LAI) and vegetation height for agricultural crops, grass, winter wheat, spring barley and maize.

2.6 Autocalibration

Automated parameter estimation was carried out for estimating vegetation and soil parameters. The shuffled complex evolution (SCE) method available in the auto-calibration tool Autocal (Madsen, 2003) was adopted following the procedures suggested by DHI (2011). Autocal was used to automatically adjust model parameters to match simulations with observed data sets such as soil water content, throughfall, etc. The global search algorithm (shuffled complex evolution algorithm) offers an effective approximation of the optimum of the objective function of the Pareto front (DHI, 2011).

As the SVAT model includes a large number of parameters not all can be estimated and it is necessary to identify the key parameters through a sensitivity analysis. The sensitivity of seven vegetation parameters were quantified; leaf area index (LAI), minimal stomatal resistance (RSC_{min}), interception capacity (C_{int}), radiation extinction coefficient (K_{ext}), albedo (α), average leaf width (w) and displacement height (z_{0s}). After the sensitive parameters are identified, a multi-objective optimization is carried out where observations are compared with corresponding simulated values, with the results being a set of Pareto solutions determined by the trade-off between multiple objectives. The multi-objective functions are aggregated by adopting a user-defined single objective function for choosing the best solution (Madsen, 2003). After the parameter estimation, model validation was carried out for assessing the credibility of the calibrated model.

The work followed a sequence of steps. Initially, the modeling was focused on simulating canopy throughfall only. Thus, soil water processes were not considered as this was not assumed to interfere with the physical process of water storage on leaf surface as well as direct evaporation of intercepted water. Transpiration from leaf stomata was not considered in the optimization although it was simulated while running the model. In later steps, modeling of transpiration and soil evaporation were also included and observations of throughfall, soil water content and actual total evapotranspiration were used for model calibration.

3. Calibration

3.1 Throughfall as observation data

Initially, throughfall was modeled using daily values of climate input data (precipitation, temperature, etc.) at both Gludsted and Frederiksborg. Below the results on model parameterization is presented.

3.1.1 Gludsted

The sensitivity analysis revealed that the most sensitive parameters for modeling throughfall at Gludsted are LAI, C_{int} and average leaf width (w). Less sensitive parameters are albedo (α) and K_{ext}, while RSC_{min} and z_{0s} are insensitive. If a relative sensitivity value of 0.02 compared to the absolute maximum scaled parameter sensitivity is used as threshold the following parameters are included in the parameter optimization at Gludsted: LAI, C_{int}, w, α and K_{ext}. The sensitivity of the vegetation height (h_{veg}) was found to be similar to that of K_{ext} and α but this parameter is deliberately be left out as it is known with relatively low uncertainty.

The parameter optimization resulted in 220 parameter set evaluations (9 loops each consisting of 22 different parameter sets) before the convergence criteria were met. In Fig. 3.1 the development in the calibration parameters with model run is shown. The best parameter set were taken for the model run that yielded the overall lowest objective function, e.i. comparison of measured and simulated TF. The estimated parameters, see Table 1, all have reasonable values. A LAI of 3.8 is within the range that has been measured at the site (Ringgaard et al., 2011). It is difficult to assess a reasonable range for the interception storage capacity parameter C_{int} as it empirically quantifies the amount of water stored on the vegetation per unit leaf area. However, a value of 0.01 mm per LAI means that a total of 0.38 mm of water can be stored in the canopy (per day). The albedo is estimated to 0.216 which is significantly higher than the measured value of 0.08 at the Gludsted site.

Table 1 Optimized parameter values for the beech stand at the Gludsted location. Values for non-optimized parameters are also included.

	Parameter	Value	Unit
Optimized parameters	LAI	3.821	$m^2\ m^{-2}$
	C_{int}	0.010	mm LAI^{-1}
	K_{ext}	0.560	-
	w	0.010	m
	α	0.216	-
Non-optimized parameters	RSC_{min}	160	$s\ m^{-1}$
	h_{veg}	17.5	m
	z_{0s}	0.025	m

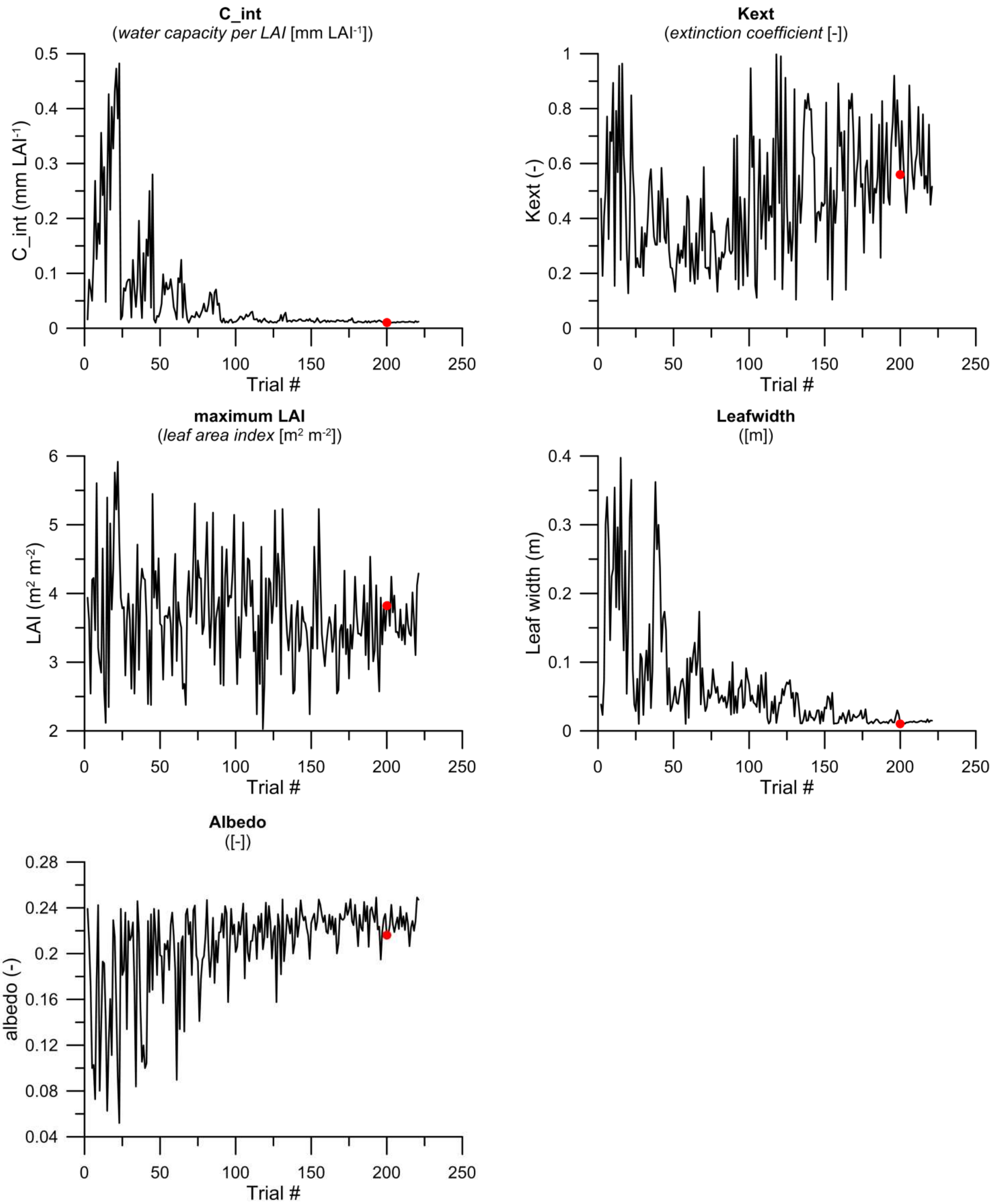

Figure 3.10 Parameter value development during optimization for the Gludsted location. Red dots mark the parameter value for the smallest error of the simulation.

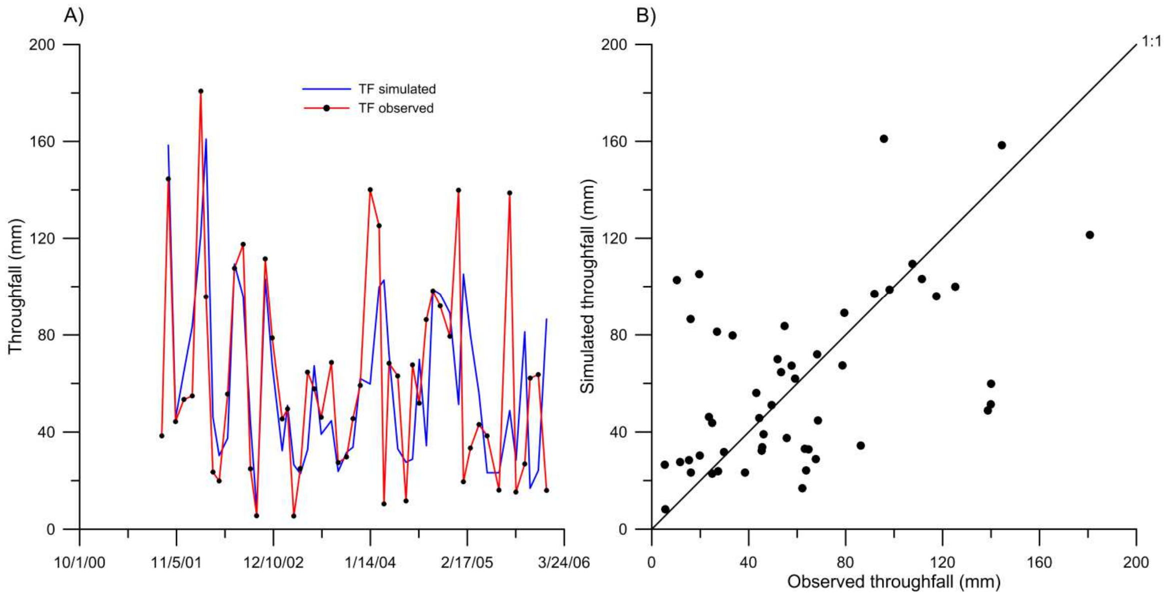

Figure 3.11 A) Comparison of the temporal variability of throughfall (mm) for the Gludsted location. Red lines with black dots are observations while the blue curve represent the simulated values B) simulated throughfall plotted against observed throughfall (mm). The 1:1 line is also shown for reference. The simulated values were obtained with the parameter set given in Table 3.

Using the estimated parameters the SVAT model is able to reproduce the temporal variability of observed TF in the period 2001-2005 satisfactorily (Fig. 3.2a). No systematic over- or underestimation is observed (Fig. 3.2b) although pronounced over- and underestimations are observed at certain periods.

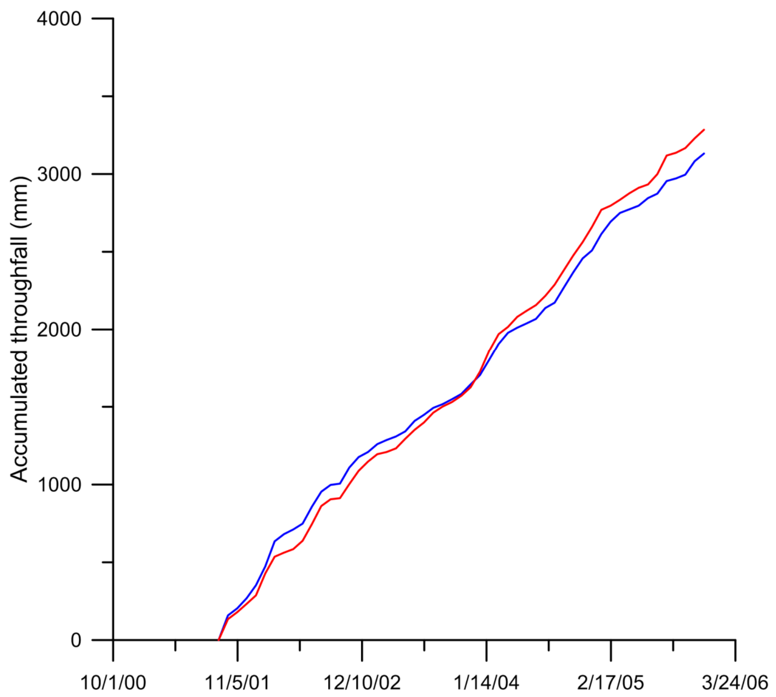

Figure 3.12 Accumulated throughfall (mm) for simulated (red) and observed (blue) for the period September 2001 - December 2005 for the Gludsted location.

The absence of any systematic over- or underestimation also results in good correspondence between accumulated amounts of TF for simulations and observations

(Fig. 3.3) for the entire period. However, the total sum of throughfall was underestimated by 4.6%. The maximum deviation was 22.6%.

3.1.2 Frederiksborg

Generally, the sensitivity analysis for Frederiksborg yielded results which are similar to those obtained for Gludsted. C_{int}, LAI and leaf width (w) are the most sensitive parameters followed by K_{ext}. Albedo, vegetation height, RSC_{min} and z_{0s} were not sensitive. Using a threshold of 0.02 of the maximum absolute scaled sensitivity, C_{int}, LAI, w and K_{ext} are included in the parameter optimization for Frederiksborg.

The parameter optimization resulted in 126 parameter set evaluations before convergence criteria were met, Fig. 3.4. The model conducted 6 loops with each loop consisting of 18 different parameter sets. The best parameter set, Table 2, was taken for the model run that yielded the overall lowest objective function, e.i. comparison of measured and simulated TF.

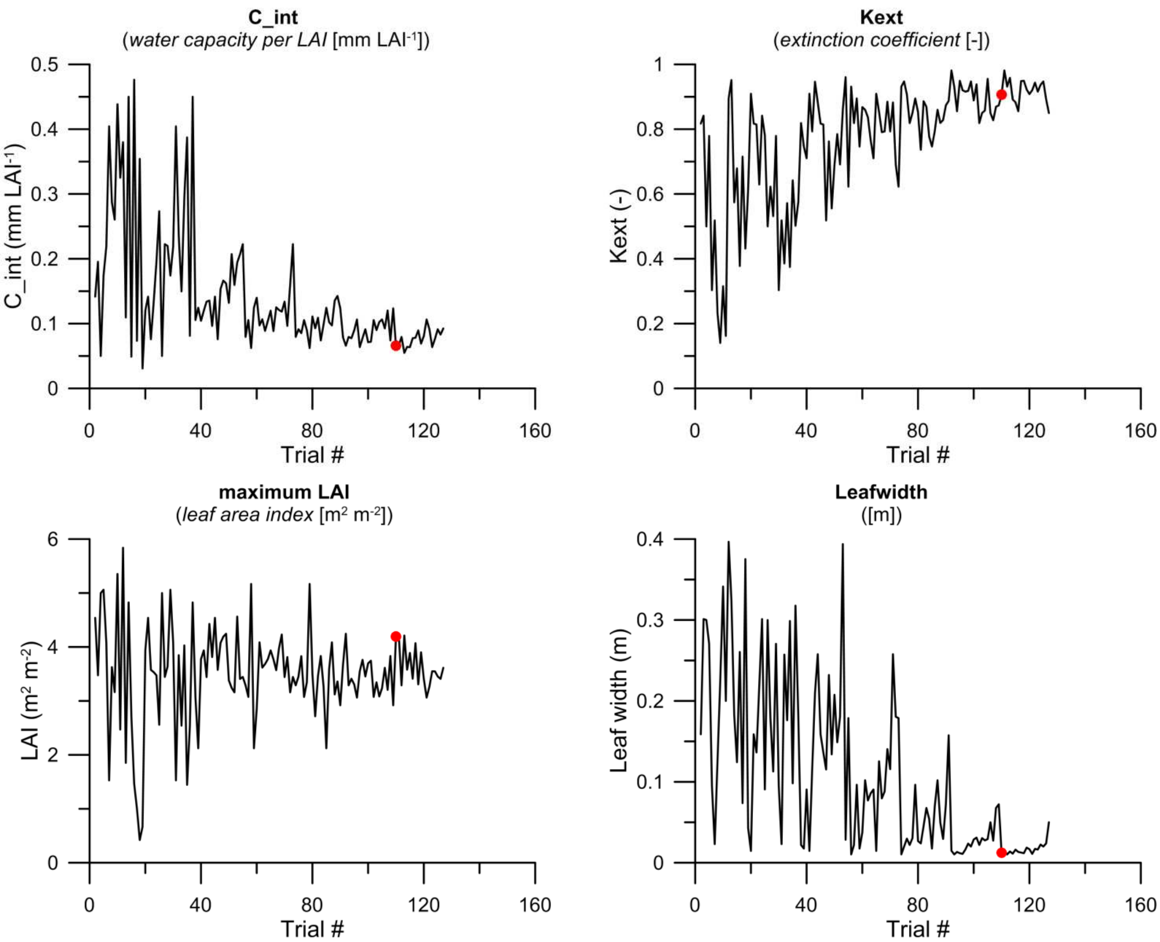

Figure 3.13 Parameter value development during optimization for the Frederiksborg location. Red dots mark the parameter value for the smallest error of the simulation.

Table 2 Optimized parameter values (in bold) for the beech stand at the Frederiksborg location. Values for non-optimized parameters are also included.

	Parameter	Value	Unit
Optimized parameters	LAI	4.195	m2 m-2
	Cint	0.066	mm LAI-1
	Kext	0.907	-
	w	0.012	m
Non-optimized parameters	RSCmin	160	s m-1
	hveg	17.5	m
	z0s	0.025	m
	α	0.1	-

The estimated LAI is close to measurements at the site (Gundersen et al., 2009) and only slightly higher than the value found for spruce (Table 1). However, C_{int} for beech is six times larger than for spruce indicating that the storage capacity of beech is six times higher than that of spruce. Also the value found for K_{ext} of 0.91 is relatively high, indicating that only 10% of the incoming radiation reaches the soil surface. A leaf width of 1.2 cm is comparable to the value found for spruce. The leaf width impacts the leaf boundary layer resistance as the resistance increase with increasing leaf width.

The calibrated SVAT model is able to simulate the temporal variability of observed TF in the period 2002-2009 (Fig. 3.5a). No systematic over- or underestimation is observed (Fig. 3.5b).

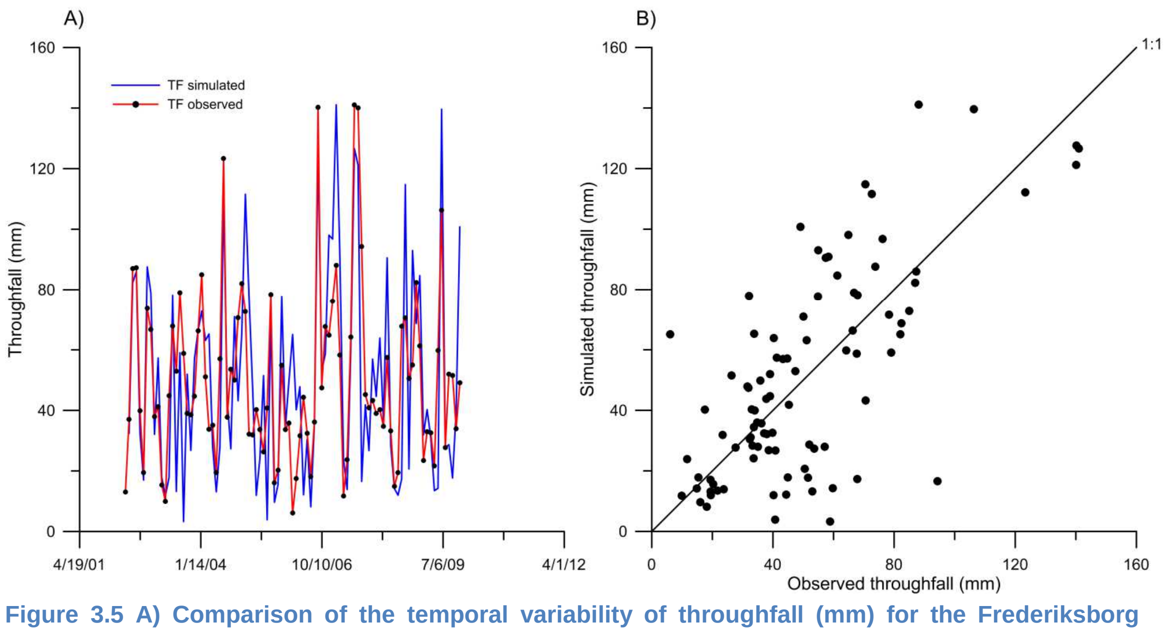

Figure 3.5 A) Comparison of the temporal variability of throughfall (mm) for the Frederiksborg location. Red lines with black dots are observations while the blue curve represent the simulated values B) simulated throughfall plotted against observed throughfall (mm). The 1:1 line is also shown for reference. The simulated values were obtained with the parameter set given in Table 3.

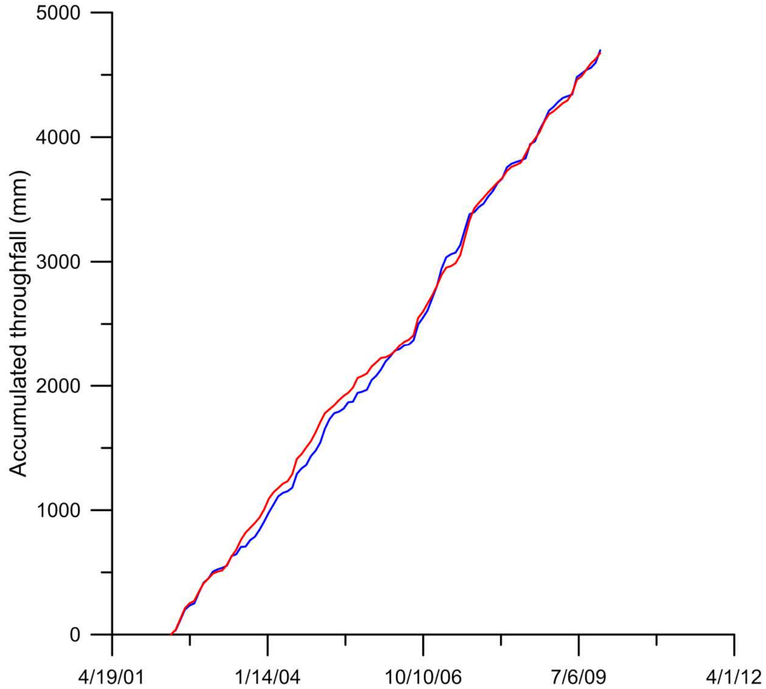

Figure 3.6 Accumulated throughfall (mm) for simulated (red) and observed (blue) for the period May 2002 - December 2009 for the Frederiksborg location.

The absence of any bias in over- or underestimation also results in very good correspondence between accumulated amounts of TF for simulations and observations (Fig. 3.6) for the entire period. The deviation of the total sum of simulated TF was 0.4% of observed TF. The maximum deviation was 13.6%.

3.2 Throughfall, soil water content and latent heat as observation data

In order to obtain estimates for other parameters than just those controlling throughfall, parameter estimation were also based on data for soil water content and actual evapotranspiration for Gludsted and soil water content for Frederiksborg. Additionally, the temporal resolution of the climate data was changed from daily to hourly as it was found difficult to obtain a physically correct description of interception storage and evaporation with a resolution of 24 hours.

3.2.1 Gludsted

The simulation of Norway spruce at Gludsted started in Jan. 2001, and the calibration was performed for a period of 9 years starting from Nov. 2001 to Dec. 2010, so the model had an eleven-month warm-up length. Periods with snow cover were excluded from the observation data sets. The identification of days with snow cover was based on temperature and surface radiance reflectivity. If the air temperature was lower than 0˚C and albedo (calculated using observations of shortwave incoming and outgoing radiation fluxes) was higher than 0.2 in December, January and February, it was regarded as covered by snow.

The following vegetation parameters were subject to sensitivity analysis: leaf area index (LAI), minimum stoma resistance (RSC_{min}), root depth (z_{rd}), interception coefficient (C_{int}), average leaf width (w) and root mass distribution (A_{root}). The van Genuchten parameters K_s, n and α for each of the three soil horizons were also included. Parameters known from the site or from literature were set constant: Vegetation height, h_{veg} = 17.5 m; soil surface roughness, z_{0s} = 0.03 m; albedo, α = 0.08, and extinction coefficient, K_{ext} = 0.5. The output targets were throughfall (Sep. 2001 - Jan. 2006), soil water content (Sep. 2009 - Dec. 2010) and latent heat flux (Dec. 2008 - Dec. 2010).

The following parameter values were identified as sensitive: leaf area index (LAI), minimum stoma resistance (RSC_{min}), interception coefficient (C_{int}), average leaf width (w), root mass distribution (A_{root}), van Genuchten parameters K_s, n and α of the top and the second soil horizons, together with the n and α of the third soil horizon.

Table 3 Parameter estimation results for Norway spruce at Gludsted.

Optimization	Parameter	Value	Unit
	LAI	4.44	m2 m-2
	Cint	0.29	mm LAI-1
	RSCmin	230	s m-1
	w	0.022	m
	Aroot	1.05	m-1
	α (0-30cm)	0.087	cm-1
Optimized	n (0-30cm)	1.33	-
	Ks (0-30cm)	5.19×10-5	m s-1
	α (30-80cm)	0.073	cm-1
	n (30-80cm)	1.77	-
	Ks (30-80cm)	8.43×10-5	m s-1
	α (>80cm)	0.059	cm-1
	n (>80cm)	1.67	-
	Root depth	1.00	m
	Albedo	0.08	-
	Kext	0.50	-
	Vegetation height	17.5	m
Non-optimized	z0s	0.03	m
	Sat. water cont. (0-30cm)	0.395	-
	Sat. water cont. (30-80cm)	0.377	-
	Sat. water cont. (>80cm)	0.355	-
	Ks (>80cm)	9.10×10-5	m s-1

The parameter optimization resulted in 240 parameter set evaluations before the convergence criteria were met. It included 8 loops where each loop consisted of 30 different parameter sets. The best parameter set that yielded the overall lowest objective function is shown in Table 3. Compared to the previous optimization, section 3.1.1, the largest difference is found for the interception coefficient C_{int}, which is 29 times higher using an hourly resolution in climate data compared to daily. This shows that the interception storage capacity is highly scale dependent. A significant difference is also found for the leaf width, w, which has doubled in this optimization. The higher value found here implies that the leaf boundary layer resistance, r_a^c, is higher with the result that transpiration is depressed, see Fig. 2.7. The values estimated for the rest of the parameters are all within plausible ranges. The values of the saturated hydraulic conductivity, K_s, are in the high end of what was expected but still reasonable values are obtained.

The simulated and observed canopy throughfall are compared in Fig. 3.7. The general trend of the time series matches well, especially in the year 2002 but also in other years. Differences during winter periods might be caused by snow melt events not described by the model.

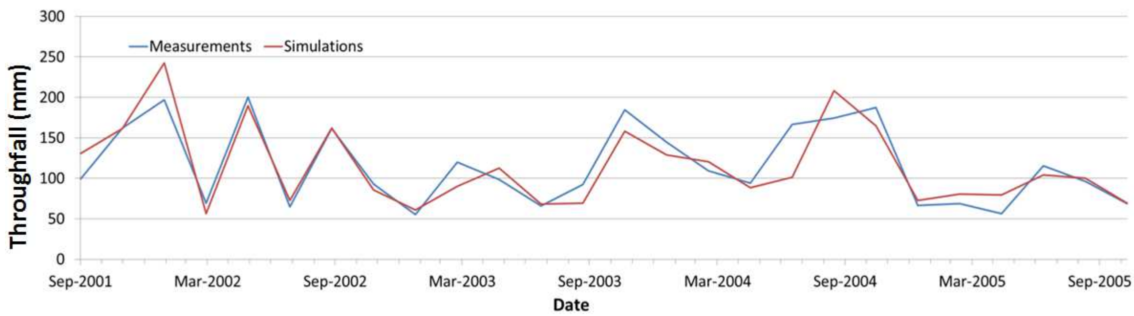

Figure 3.7 Comparison between simulated and observed canopy throughfall in the calibration period (Sep. 2002 - Jan. 2006).

The simulated and observed accumulated actual evapotranspiration (EA) are shown in Fig. 3.8. The simulated annual total EA is almost identical to the observed. During spring, the simulated EA is slightly lower than the observations, while during summers the simulated EA is higher than observed. A regression analysis on the simulated and observed daily EA showed that the R^2 equals 0.83.

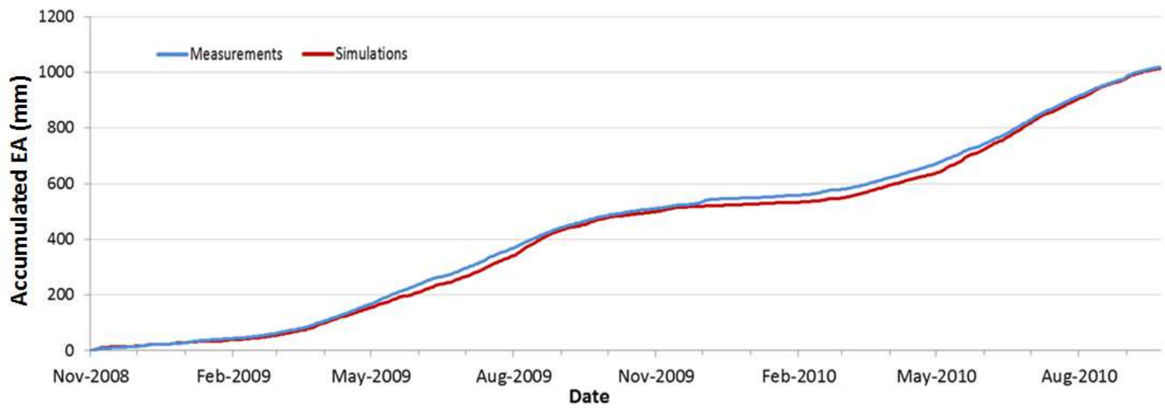

Figure 3.8 Comparison between simulated and observed accumulated EA in the calibration period (Nov. 2008 - Nov. 2010).

The observed and simulated soil water contents are compared in Fig.3.9, with the regression results shown in Table 3.4. The correlation coefficient R^2 is in all cases above 0.97, indicating an acceptable match.

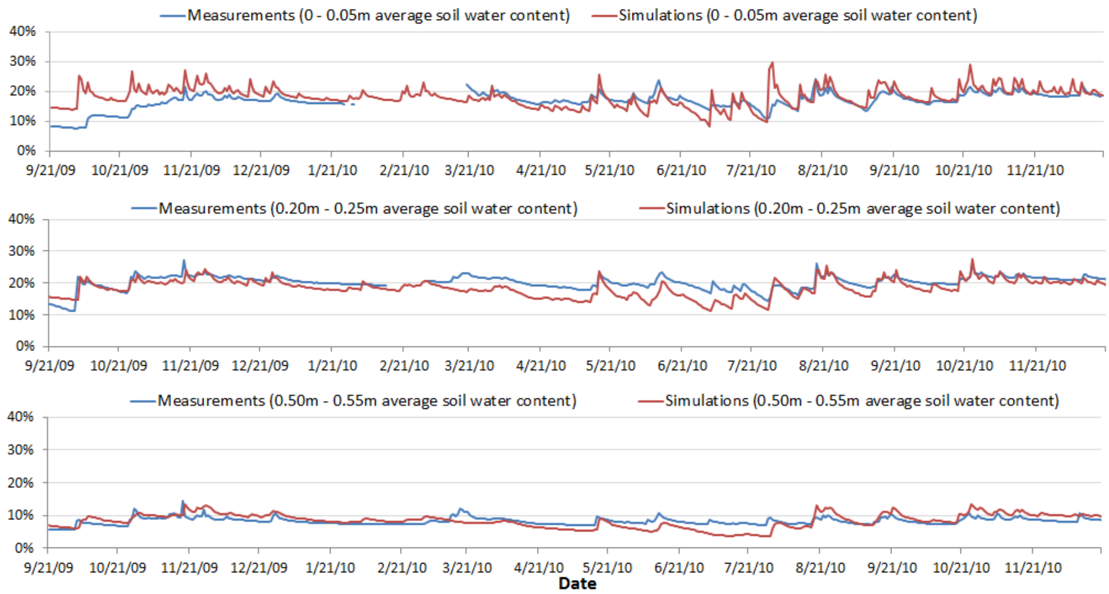

Figure 3.9 Plot of simulated and observed average soil water content at three depths during the model calibration period (Sep. 2009 - Dec. 2010).

Table 4 Correlation coefficient (R^2) of simulated and observed average soil water content during the model calibration period.

Sample depth	R2
0 m - 0.05 m	0.97
0.20 m - 0.25 m	0.98
0.50 m - 0.55 m	0.99

Validation on the accumulated EA was carried out for the period Jan. 2011 - Dec 2011 (shown in Fig. 3.10). The observations are well matched in the first 8 months, but in the last 4 months the model overestimated the EA by around 8.6%, which was not in accordance with the situation found in the model calibration. This may be due to possible errors in the observed EA. The correlation analysis on daily EA showed that the R^2 equals 0.9, and the scatter plot is shown in Fig. 3.11.

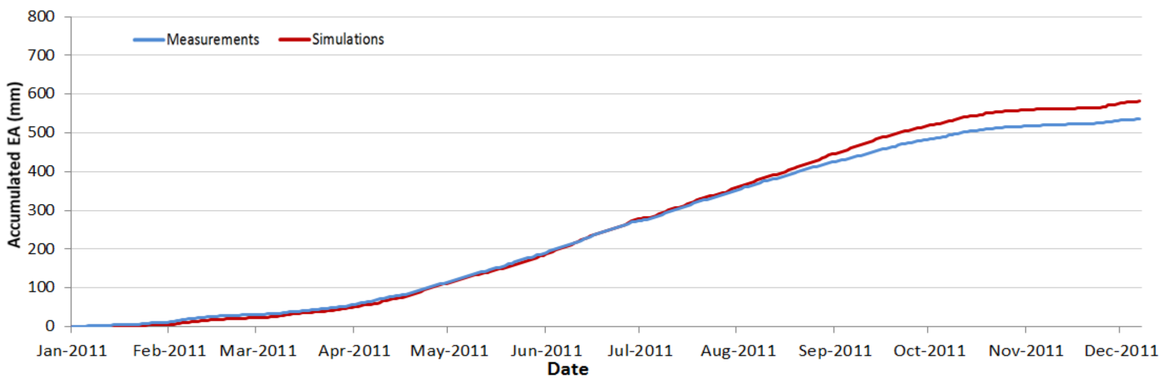

Figure 3.10 Comparison between accumulated simulated and observed EA during the model validation period (2011 - 2011).

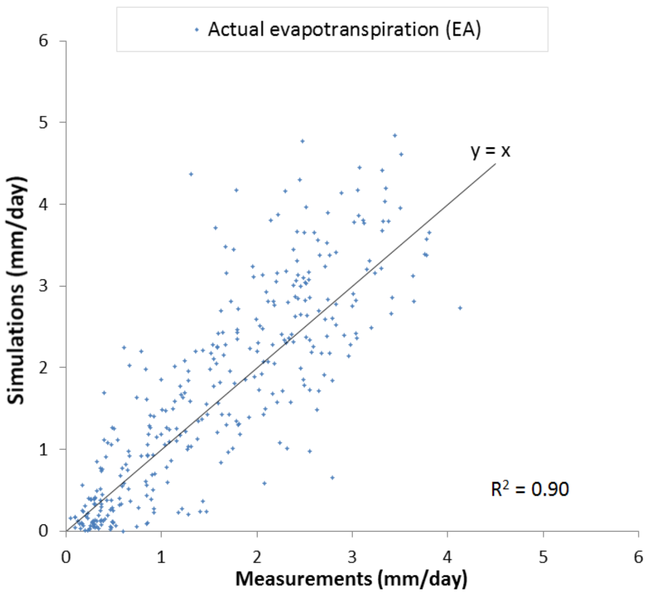

Figure 3.11 Plot of simulated and observed daily EA during the model validation period (Jan. 2011 - Dec. 2011). The correlation coefficient (R^2) equals 0.90.

3.2.2 Frederiksborg

The simulation of the beech in Frederiksborg started in Jan. 2000, and the calibration was performed for a period of 8 years from Jan. 2001 to Dec. 2008. Periods with snow cover were excluded. As no albedo observations or snow records were available at the Frederiksborg station, all observations from December, January and February were excluded.

The following vegetation parameters were subject to sensitivity analysis: leaf area index (LAI), minimum stoma resistance (RSC_{min}), root depth (z_{rd}), interception coefficient (C_{int}), average leaf width (w) and root mass distribution (A_{root}). The van Genuchten parameters K_s, n and α for each soil horizon were also included. Other parameters were set to constant based on observations or literature values: vegetation height, h_{veg} = 19.8 m; soil surface roughness, z_{0s} = 0.03 m; albedo, α = 0.18, and extinction coefficient, K_{ext} = 0.5. The output measures were canopy throughfall (May 2001 - Nov. 2006) and soil water content (Jan. 2001 - Dec. 2008). Parameters were considered insensitive if their sensitivity was less than 0.02 times the maximum sensitivity measure.

The following parameters were identified as sensitive: leaf area index (LAI), minimum stoma resistance (RSC_{min}), interception coefficient (C_{int}), average leaf width (w), root mass distribution (A_{root}), K_s of both soil horizons, and the van Genuchten parameter α of the first soil horizon. These parameters were subject to adjustments through the parameter estimation.

Table 5 Parameter estimation results for beech at Frederiksborg.

Optimization	Parameter	Value	Unit
Optimized	LAI (max.)	3.15	m2 m-2
	Cint	0.14	mm LAI-1
	w	0.025	m
	Aroot	2.50	m-1
	α (0-50cm)	0.019	cm-1
	Ks (0-50cm)	2.32 ×10-6	m s-1
	Ks (>50cm)	1.75×10-7	m s-1
Non-optimized	Root depth	1.50	m
	Albedo	0.18	-
	Kext	0.50	-
	RSCmin	100	s m-1
	Vegetation height	19.80	m
	z0s	0.03	m
	Sat. water cont. (0-50cm)	0.427	-
	Sat. water cont. (>50cm)	0.379	-
	n (0-50cm)	1.90	-
	α (>50cm)	0.03	cm-1
	n (>50cm)	2.00	-

The parameter optimization resulted in 210 parameter set evaluations before convergence criteria were met. It included 7 loops with each loop consisting of 30 different parameter sets. The best parameter set that yielded the overall lowest error for the objective function is shown in Table 5. Comparing the soil paramters in Table 3 and 5 reveals that the soil in Frederiksborg is less permeable as the saturated hydraulic conductivity is one to two orders of magnitude lower for Frederiksborg. Also the estimate of α is significantly lower reflecting a much higher entry pressure for air. The value specified for n in the two soil horizons is probably in the high end of what is expected resulting in a relatively sharp drainage curve. As the soils at Frederiksberg are clayey one would expect a more gradual drainage reflected by lower n-values. However, as the n-parameter was found to be relatively insensitive for the results it is assumed to be of less significance.

The observed and simulated canopy throughfall are compared in Fig. 3.12. The simulated canopy throughfall was generally higher than the observations; however, the dynamics of the two time series match to an acceptable degree. It should be taken into account that the measurements do not include stem flow which can be substantially for beech. In a Danish beech forest stem flow has been estimated to 2% and 6% of the measured throughfall amount in the growing and the dormant season, respectively (Dalsgaard, 2007). Also, there were a few episodes of overflow in the collection system at heavy rains causing too low throughfall measurements.

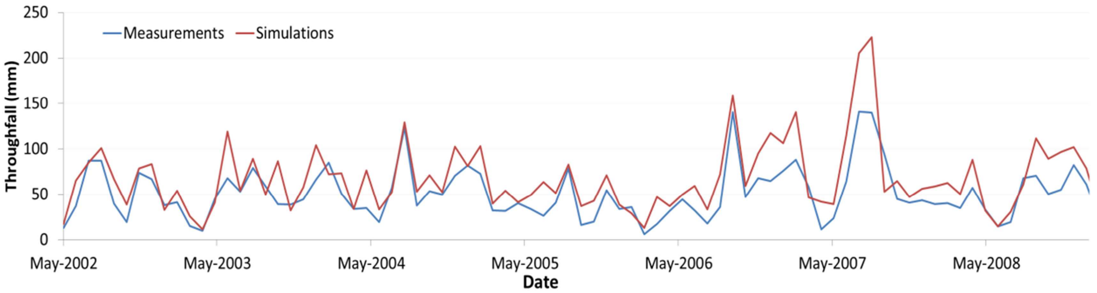

Figure 3.12 Comparison between simulated and observed canopy throughfall during May 2002 - Nov. 2009.

The average soil water contents at four depth intervals are shown in Fig. 3.13, in which the simulations satisfactorily match the dynamics of the observed values at all the depths.

Figure 3.13 Comparison between simulated and observed average soil water content at four depths during the calibration period.

The estimated parameters were utilized in the model validation for the period Jan. 2009 - Dec. 2009. The average soil water contents at four depths were sampled and compared. The time series of simulated and observed soil water contents are shown in Fig. 3.14. The correlation coefficients (R^2) are shown in Table 6.

The simulated average soil water content between 0 - 0.5 m depth matched the measurement best with an R^2 of 0.90, followed by the simulations for the depth interval 0 - 0.2 m with the R^2 of 0.87, and 0 - 0.75 m with the R^2 of 0.86. The model simulations of the deeper horizon match observations worse than at the top soil. The average soil water content between 0 - 1 m was underestimated to a higher degree with the R^2 of 0.36.

The observed and simulated canopy throughfall are shown in Fig. 3.15. The observed throughfall are lower than the simulations during the summer and the winter, while they matched better during the spring. The validation is considered as acceptable, considering the significant uncertainties on the observations.

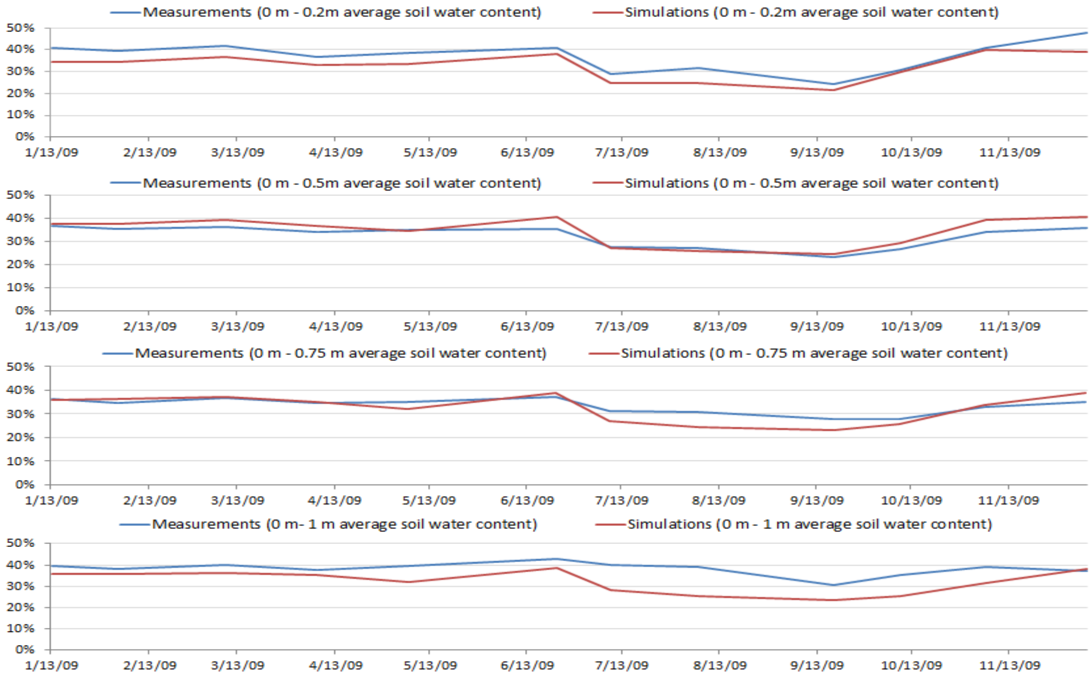

Figure 3.14 Comparison between simulated and observed average soil water content at four depths during the validation period.

Table 6 Correlation coefficient (R2) for simulated and observed average soil water content at four depths during the model validation period.

Sample depth	R2
0 m - 0.2 m	0.87
0 m - 0.5 m	0.90
0 m - 0.75 m	0.86
0 m - 1.0 m	0.36

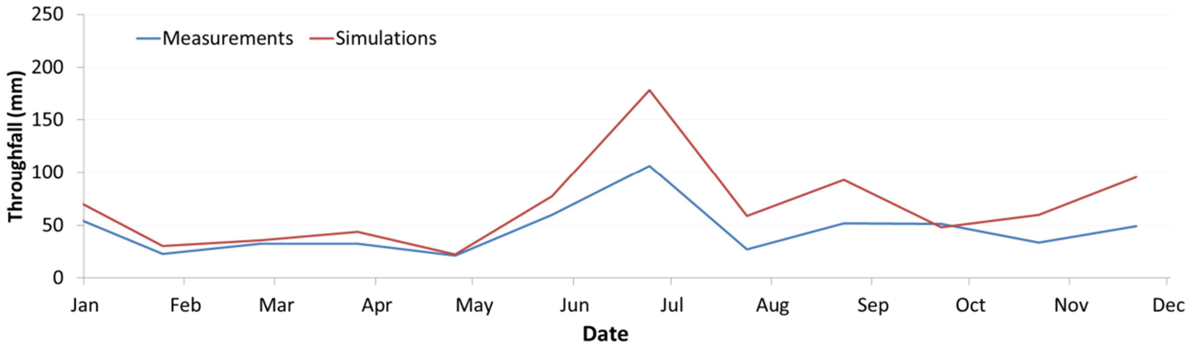

Figure 3.16 Comparison between simulated and observed canopy throughfall during the validation period.

3.3 Parameter sets for different vegetation types

In Table 7 estimated vegetation parameters for spruce, beech, willow and the four crops are listed. Parameters for willow are based on Bruge (2013) while the parameters representing grass, wheat, barley and maize are derived from Mollerup (2011). Since only the parameters for spruce and beech have been estimated using observations from field sites the parameter values of the other vegetations are associated with considerable uncertainty. It should be noticed that the properties are only constant for spruce. LAI and vegetation height exhibit strong seasonal variations for most of the other vegetation types, see Figures 2.8 and 2.9. Also root depth varies over season for the crops. C_{int} for spruce is higher than for the other vegetation implying the more water can be stored per unit LAI.

Table 7 Vegetation parameters for different forest types and crops. Root depths for different soil types are listed.

	Spruce	Beech	Willow	Grass	W. Wheat	S. Barley	Maize
Albedo, α (-)	0.08	0.18	0.2*	0.185*	0.195*	0.19*	0.18*
Veg. height, hveg (m)	17.5	19.8	3.96*	0.275*	0.8*	0.75*	2.0*
LAI (m2 m-2)	4.44	3.15*	6.0*	5.0*	5.0*	5.0*	3.5*
Cint (mm LAI-1)	0.29	0.14	0.2	0.05	0.05	0.05	0.05
RSCmin (s m-1)	230	100	30	110	110	110	110
Leaf width, w (m)	0.022	0.025	0.01	0.02	0.02	0.02	0.02
Ext. coeff., Kext (-)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
z0s (m)	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Aroot (m-1)	1.05	2.50	2	0.25	0.25	0.25	0.25
Root depth, JB1 (m)	1.00	1.50	1.2*	0.5*	0.5*	0.5*	0.5*
Root depth, JB4 (m)	1.00	1.50	1.2*	0.6*	0.9*	0.85*	0.85*
Root depth, JB6 (m)	1.00	1.50	1.2*	0.6*	1.2*	0.9*	1.0*

* Value varies over season. Maximum value listed.

4. Evapotranspiration and groundwater recharge

Results on the water balance of each of the vegetation's were obtained for two groundwater depths at the Gludsted site (Fig. 4.1). First, results for the case where groundwater is located 50 cm below ground surface are presented. According to Table 7, the root depth for all vegetation types is minimum half a meter. In this analysis the roots have been truncated at half a meter such that the roots just reach the groundwater but don't extend below the groundwater table. The vegetation is, however, well supplied with water and the resulting flux of water to the atmosphere is considered as representative of the potential evapotranspiration.

In the second case the groundwater level is fixed at a depth of 10 m below ground surface. Considering the sandy soil type at Gludsted, see Table 3, this ensures that no upward flow of groundwater will take place. Hence, the two set of results are expected to encapsulate the range of results obtained in a catchment simulation.

The analysis is based on results from a three year simulation period, from the December 9, 2008 to December 8, 2011.

4.1 Total evapotranspiration and groundwater recharge

In Figure 4.1 the total evapotranspiration and the groundwater recharge for the seven vegetations are presented. In the case of high groundwater level (left), spruce has the highest evapotranspiration, followed by beech, willow, grass, winter wheat, barley and maize respectively. The total annual evapotranspiration for spruce is estimated to approximately 750 mm/yr. As the average precipitation equals 918 mm/yr in the same period, this leaves less than 200 mm/yr for groundwater recharge. If the other extreme, maize, is considered, the total ET is less than 450 mm/yr leaving nearly 500 mm/yr for groundwater recharge.

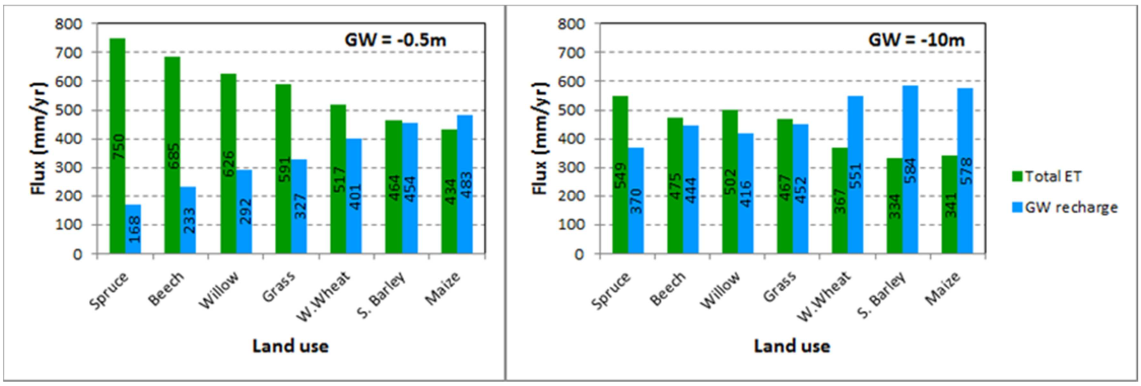

Figure 4.1 Total evapotranspiration and groundwater (GW) recharge at a groundwater table at half a meter below soil surface (left) and 10 m below soil surface (right), calculated for Gludsted.

The depth to the groundwater table has a relatively small effect on the relative order of the total evapotranspiration, see Figure 4.1 (right), however it causes important changes in the absolute evapotranspiration rate. The deeper the groundwater table, the smaller is the total evapotranspiration. For instance, evapotranspiration of spruce decreases by 200 mm when changing the groundwater table from -0.5 m to -10 m. There are some exceptions where the order mentioned above is modified, e.g., evapotranspiration of willow is higher than beech when GWT = -10 m.

4.2 ET components

To explain these variations, the ET components (Fig. 4.2) should be analyzed, i.e., interception loss, transpiration, and soil evaporation, for each vegetation. Evaporation from ponded water is negligible for the coarse soil type used and evapotranspiration from SZ is zero as the roots are truncated at the groundwater table.

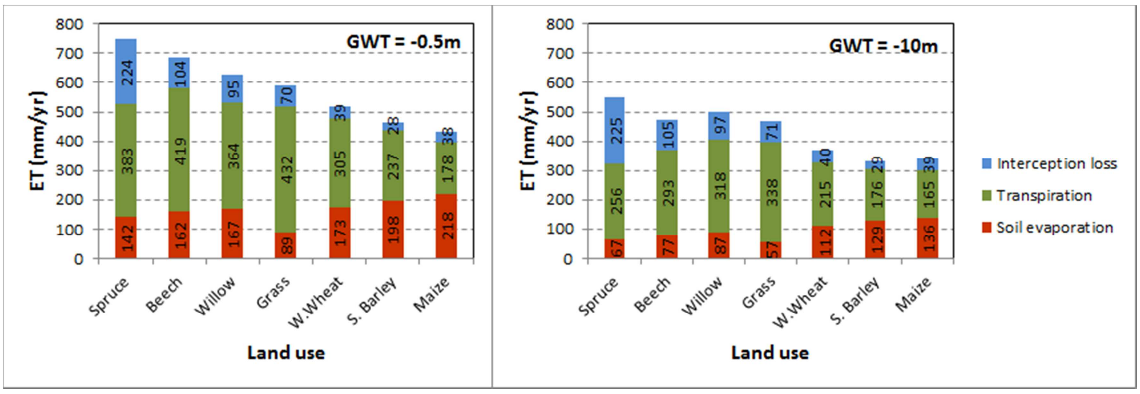

Figure 4.2 Soil evaporation, transpiration and interception loss at groundwater table depths of 0.5 m (left) and 10 m (right). Both represent the Gludsted site.

Compared to the situation with a groundwater table at 10 m depth, higher transpirations are found for shallow groundwater table where water is constantly available for the roots. Transpiration is the major component of the total evapotranspiration in all cases except for maize. The highest transpiration is found for grass followed by beech and spruce. The lowest transpiration is found for maize and spring barley. Both have a relatively short period with vegetation. Additionally, maize grows in a period where the available energy is less than the maximum value at summer solstice.

When GWT = -10m, transpiration from grass is still the highest but transpiration from willow is now higher than transpiration from spruce and beech. By comparison of the parameters used, Table 7, LAI and RSC_{min} seem to be the key parameters. When the water availability decreases, transpiration decreases more for spruce and beech than for willow since willow have a very small RSC_{min} and a high leaf area index which encourage transpiration. This variation of transpiration explains why total evapotranspiration for willow is higher than evapotranspiration of beech at deep groundwater level.

At a groundwater depth of 0.5 m soil evaporation is the second most important component of the total evapotranspiration for all the vegetation types but spruce. Soil evaporation varies between 7% (grass) to 24% (maize) of the total rainfall. The position of the groundwater table has a strong influence on the absolute level of soil evaporation: the deeper the groundwater table is, the dryer the root zone gets and the lower is the soil evaporation. Whatever the groundwater level, agricultural crops, characterized by relative long periods with no or sparse vegetation, have the highest soil evaporation.

4.3 Temporal dynamics in evapotranspiration

Interception loss is a very important component of the water balance of forests since their interception capacity is high compared to agricultural crops. Interception is, of course, independent of the groundwater level. Spruce has by far, the highest interception loss. Spruce has a high and constant LAI, and a relatively high interception coefficient (C_{int}). Therefore, even though the energy available for evaporation is low during winter, interception loss is relatively high. This is seen on Figures 4.3 and 4.4 where the average actual evapotranspiration over the three year simulation period is presented for each of the seven vegetation types. ET from spruce (black line) is seen to be relatively high during winter, in the order of half a mm/day. Hence, during the period November-February approximately 60 mm is evaporated from the spruce while the evapotranspiration from the other vegetation types is negligible. The reason why total evapotranspiration from spruce is higher than for other vegetation types is primarily that the evaporation from spruce is high during winter season (November to April). During summer, ET from both beech and willow is higher than from spruce.

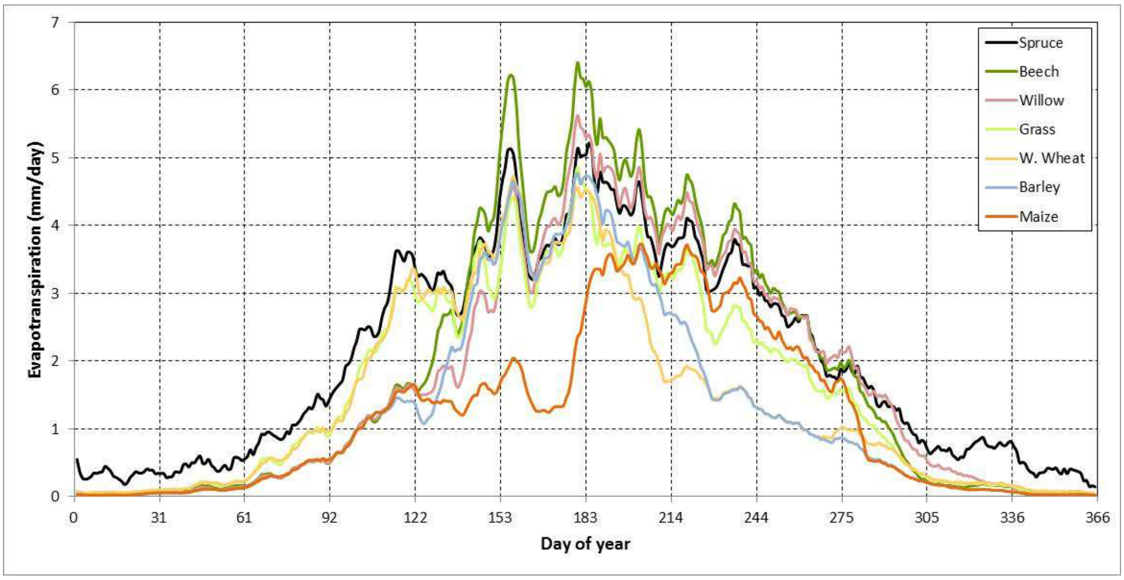

Figure 4.3 Annual cycle in total evapotranspiration for seven vegetations. Groundwater table is in all cases located at 0.5 m below soil surface. Data averaged over the period 2009-2011 for Gludsted.

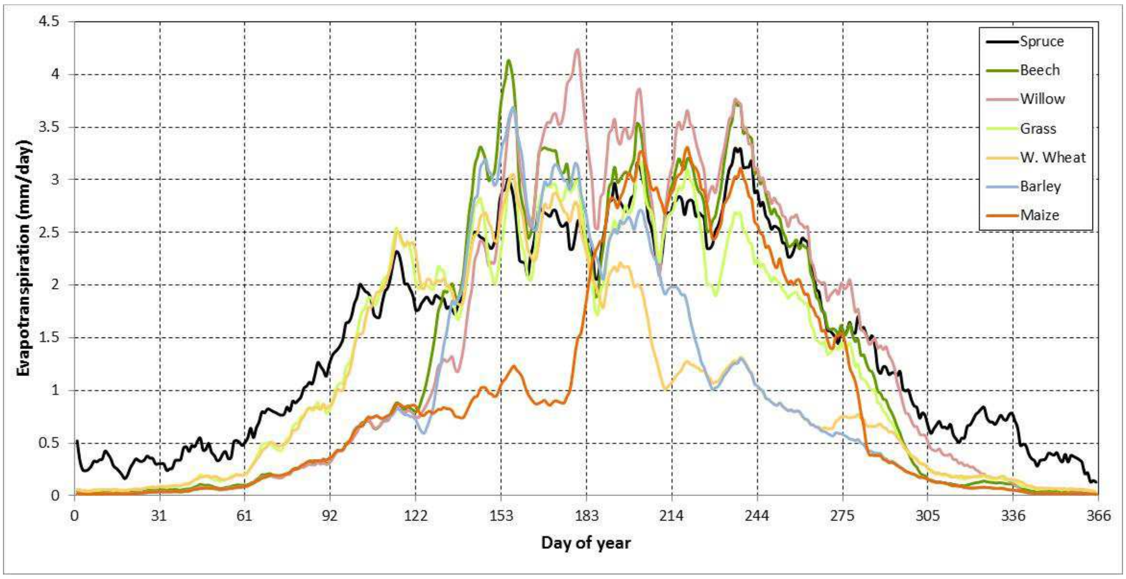

Figure 4.4 Annual cycle in total evapotranspiration for seven vegetations. Groundwater table is in all cases located at 10 m below soil surface. Data averaged over the period 2009-2011 for Gludsted.

However, actual evapotranspiration during summer, when all vegetation types are in full growth, is relatively similar. The main differences are observed during periods where some of the vegetation types have low LAI. This is clearly seen from Figures 4.3 and 4.4. ET from maize is low until end of June where the crop starts to grow. Until then ET is controlled by soil evaporation which is seen to be significantly higher at a groundwater depth of 0.5 m compared to 10 m. For winter wheat and spring barley a decline in ET is observed after harvest which takes place in late July and early August, respectively, see Figure 2.9. During late summer and fall ET from these two crops are significantly lower than for the remaining vegetation types.

5. Discussion

Initially, only parameters affecting throughfall were estimated using auto-calibration. The modeling of throughfall was based on daily climate input, including precipitation, global radiation, temperature, relative humidity, wind speed and atmospheric pressure. However, it was realized that is was difficult to obtain a satisfying description of interception dynamics at a temporal scale of 24 hours. Within this period the interception storage may be emptied several times, if it rains more than once and sufficient energy is available. Therefore, a time scale less than the time it takes to empty the interception storage capacity is required to obtain a physical satisfactory description of the interception loss. Using a temporal resolution of climate data input of one hour was found to be satisfactorily.

It was also realized that if the impact of land use change should be assessed, quantification of other evapotranspiration processes than just interception evaporation are required. Therefore, it was necessary to extend the model such that also transpiration and soil evaporation were considered and the parameters controlling these processes were estimated. Based on the estimated parameters and the resulting predictions of total evapotranspiration it is assumed that acceptable descriptions of evapotranspiration from both spruce and beech have been obtained. The difference in total evapotranspiration between spruce and beech obtained from our simulation (75 mm/yr and 65 mm/yr for the deep and shallow groundwater levels, respectively) were less than those difference found in other studies comparing the species at the same location (Christiansen et al. 2006; 2010); however these relied on data from shorter simulation periods. It was also found that the difference in groundwater recharge between alternative land use types was largest in the case of deep groundwater. For example, the difference between groundwater recharge for spruce and spring barley is 285 mm/year for deep groundwater and 175 mm/year for shallow groundwater. Hence, for sandy soils afforestation on sites with large depth to the groundwater table will result in significant reduction in groundwater recharge whereas the effect is moderate in areas with shallow groundwater.

Parameter estimates for the most sensitive vegetation parameters have been assessed for both forest and crops. For spruce and beech forest, data have been available to calibrate the relevant parameters and the parameter sets for these two vegetation types are therefore considered to be more reliable than those used for the vegetation types where no calibration data have been used. Hence, the uncertainty on the vegetation parameters representing willow and the agricultural crops is considered to be higher. To reduce this uncertainty an analysis of flux data from agricultural sites and a willow plantation is required. The uncertainty on the parameter estimation could also be reduced if data was available from sites located close to each other such that the climatic conditions and soil properties were comparable. Additional, an assessment of the parameter estimation uncertainty could be an element in future studies.

However, despite the deficiencies of the parameter estimation the validation tests generally showed that the model was able to reproduce independent observations of throughfall, actual evapotranspiration and soil water content. This increases the reliability of the parameter estimates. Moreover, the analysis of the model results showed that it may not only be the actual value of the estimated parameters that controls the differences between the evapotranspiration from the different vegetation types. The timing of the growing periods and the periods where the vegetation contain leaves also impact the level of evapotranspiration significantly. And since the growing period and the time of harvest is known relatively precisely, the uncertainty on the predicted evapotranspiration rates might not be as high as initially considered.

6. Conclusions

The following conclusions are drawn from the study:

(1) The energy based MIKE SHE SVAT model is able to represent the processes dominating evapotranspiration from forest (both conifer and broadleaf).

(2) Modeling of interception storage and evaporation requires input data and model time steps with a resolution in the order of hours if the effects of rainfall dynamics at a particular site should be captured.

(3) To estimate the model parameters controlling both soil evaporation, transpiration and interception loss, data on soil moisture content, throughfall and actual evapotranspiration should be available. In the case where no data on actual evapotranspiration was available the stomata resistance controlling transpiration was insensitive and hence not possible to estimate.

(4) Based on the model formulation and the available observation data it was possible to estimate physically reasonable vegetation parameters that resulted in acceptable validation tests.

(5) Water balances at plot scale indicate that higher evapotranspiration can be expected from spruce compared to beech. Lower ET is expected from willow and grass while the evapotranspiration rates from wheat, barley and maize are lowest. The differences depends on water availability (groundwater depth), and are found to be significant. Differences in total annual ET between spruce and maize are estimated to 325 mm/yr and 210 mm/yr for groundwater depths of 10 m and 0.5 m, respectively. Hence, the impact of vegetation type on groundwater recharge is potentially significant.

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Bilag 2:

Modeling of afforestation in a sandy and a clayey catchment: impact of forest type and coverage on groundwater resources

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Content

Abstract

Using a physically based and spatially distributed hydrological model with an energy based description of evaporation and transpiration processes (MIKE SHE SVAT), two large scale models have been established; one for the Skjern catchment in Western Denmark dominated by sandy soils and one for the Lejre area in Eastern Denmark dominated by clayey soils. Several land use scenarios have been defined using forest (beech and spruce stands) and agricultural crops (willow SRC, grass, corn, wheat and barley) in different combinations and area coverage to test the impact of forest type and coverage on water resources. The model is found to give a reliable representation of the exchange processes between groundwater, soil water, the vegetation and the atmosphere. The results from 10-year model runs of different land use scenarios show that if existing conifer forests are replaced by broadleaf forests, a significant increase in groundwater recharge and groundwater level is expected. It is also shown that it is possible to double the area covered by forest without compromising the groundwater resources or the minimum stream discharge if afforestation is carried out with broadleaves and the present conifer forest simultaneously is substituted by broadleaf forest. If the land use of the entire catchment is changed from agriculture to forest, significant reductions in groundwater level and stream discharge may be expected, especially if the forest consists of conifer trees. The results indicate that the impact of increasing the forest area on stream discharge is stronger for the Lejre area than for the Skjern area. In Lejre the shallow geology is dominated by clayey moraine deposits which limit the hydraulic conductivity of the sub-surface. Hence, if groundwater recharge is increased the extra water is prone to discharge through near surface routes such as overland flow or drain flow. In contrast, the sandy soils in Skjern enable the additional groundwater recharge to flow through the groundwater aquifers. The effect of land use change on the groundwater resources will therefore be larger at the Skjern river catchment than at the Lejre catchment.

1 Introduction

As the Danish drinking water supply is almost totally based on groundwater, it is generally recognized that retaining its sustainability and quality is of critical importance. Land-use is an important factor influencing the catchment water balance and changes in land-use is an on-going process in many countries. The total change of the forest growing stock has been positive in Europe in the 20th century (Kankaanpää and Carter, 2004). Spiecker (1999) studied and summarized data on forest growth from twelve countries throughout Europe. He found accelerated growth in forest coverage in most countries since the 19th century, which has been supported by many recent studies. Forest Europe (2011) estimated the forest coverage in all European countries (shown in Fig. 1.1), and found that during the 20th century the average growth rate in forest area was 0.37% in the European Union and 0.15% in Northern Europe. Alone since 1950 the European forest area increased 25% according to a new analysis (Fuchs et al., 2012). Around half of the forested areas in Europe are covered by coniferous forest, and the rest is equally shared by deciduous forest and mixed forest. Most land-use predictions generally agree that the trend of afforestation in Europe will continue in the coming decades.

In Denmark, the coverage of agricultural crops is one of the highest in Europe. However, forest has to some extend recovered from severe deforestation in history, and the forest coverage has been more than doubled during the last century. According to a national forest assessment (Nord-Larsen et al. 2009), Fig. 1.2, approximately 14% of Denmark is covered by forest. Of the forest in the country, 44.5% is coniferous, 39.5% is deciduous, 12.5% is mixed, while 3.5% is of unknown type. The most widespread species are spruce and beech that cover around 16% and 13% of the total forest area, respectively. The capital region has the highest forest coverage (17.3%), followed by the regions of central Jutland (15.7%), northern Jutland (13.3%), Zealand (11.8%) and southern Denmark (11.3%).

Since the 1990s, a new national forest program and new policies that emphasize ecological and cultural arguments on afforestation and forest management have been introduced. In the national forest program, an important objective is that ‘forest landscapes cover 20-25% of Denmark after one tree-generation in 80-100 years’, with a high priority on developing a multifunctional forestry, an important part of which is the promotion of the share of domestic deciduous trees in the forest type structure (Ministry of the Environment, 2002). To promote the implementation of the national forest program, some supporting policies have been made: the new Forest Act was launched in 2004; the governance structure was simplified such that key responsibilities on forest protection was moved from county councils to the central government; financial incentives, e.g. new grants schemes, were carried out; and more studies on relevant subjects are encouraged. In recent years, water protection has become an important objective in the national forest program and water companies are often engaged in afforestation projects.

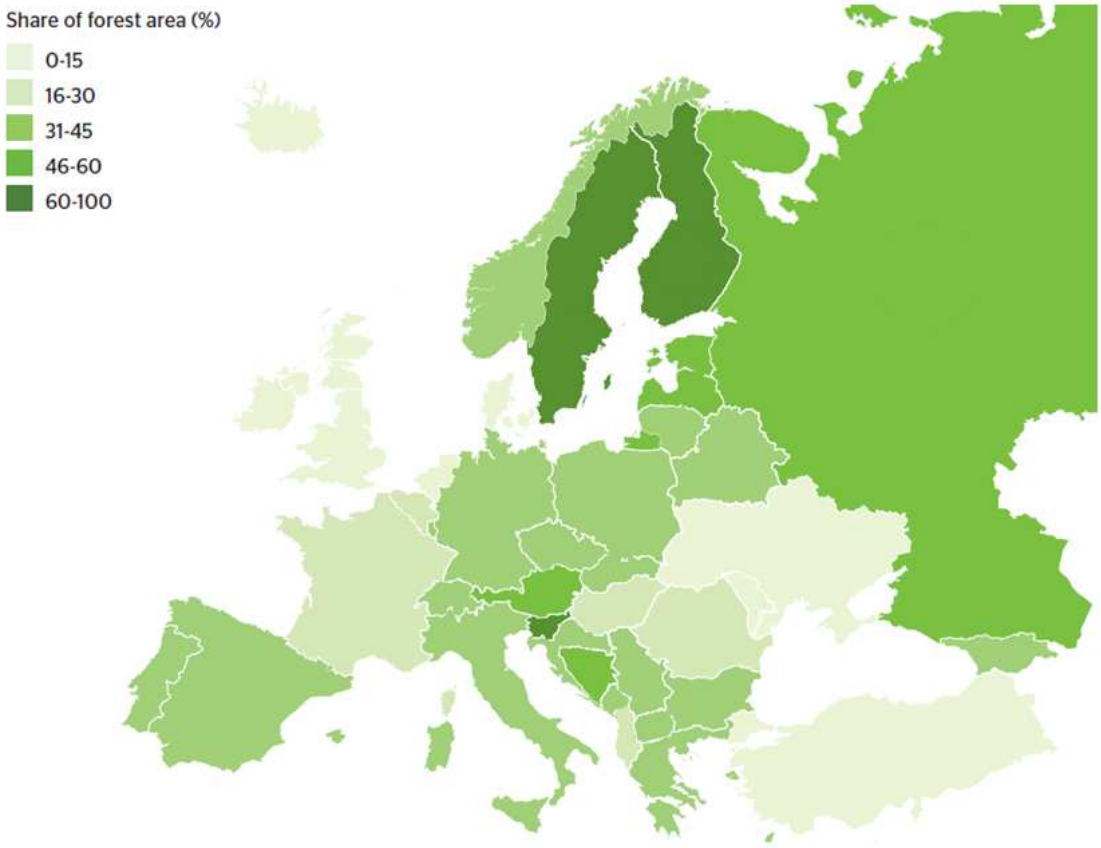


Figure 1.1 Forest coverage of European countries (Forest Europe 2011).

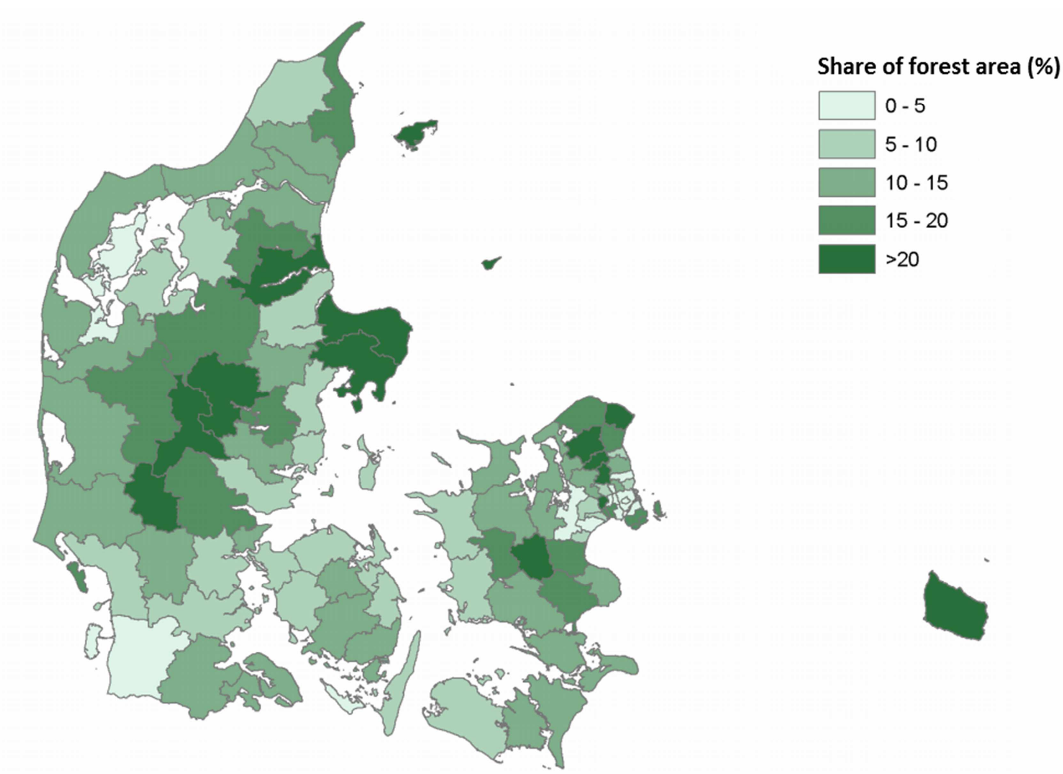


Figure 1.2 Forest coverage by municipality in Denmark (Nord-Larsen et al., 2009).

Climate change has increased the focus on renewable energy sources, including short rotation coppice (SRC) for production of biomass for heat and/or electricity. SRC has been identified as the most energy efficient carbon conversion technology to reduce greenhouse gas emissions (EC, 2005) (Styles and Jones, 2007). Heller et al. (2004) suggest that the environmental impacts from producing electricity with willow biomass energy crops are similar to using woody residues and that the pollution prevented is comparable to other renewable energy sources (solar and wind). A rapid increase of SRC in several European countries has been projected already in the short-term (Dimitriou et al., 2009). SRC, which include species like willow and poplar, are perennial crops that differ from arable crops in several ways. In particular, SRC plantations will remain in place for a number of years (10 to 25 years). Plants are generally higher than standard crops and they are deeper rooted. Additionally, once established, SRC requires no annual soil cultivation and considerably less agrochemical input. As a result of the lower nitrogen fertilizer applications, SRC has a much lower carbon footprint compared to food or biofuel production from annual arable crops. The evapotranspiration rates reported in the literature for willow and poplar SRC seems in most cases to be higher than for arable crops, but such values vary noticeably and are related to site-specific factors such as soil type, temperature, groundwater level, precipitation, plant species or clones, and the age of the crop. Despite of this, effects on water balances on catchment level have not been reported or justified yet (Dimitriou et al., 2009).

Several approaches have been undertaken in studies worldwide in attempts to understand the hydrological implications of land-use changes. Experimental comparison can be applied if the long-term information on land-use and hydrological data are available. The preliminary research by Law (1956) identified increases in water loss associated with afforestation practices in catchments in the UK. In the study by Bell et al. (1990), a reduction in groundwater level was found in pastures of Western Australia after part of them were replaced by forest, and increases in the magnitude of the reduction were found with the rise of the forest coverage. Bosch and Hewlett (1982) reviewed a total of 94 paired catchment studies worldwide to determine the effect of land-use change on water yield. They found that in most cases the reductions in forest coverage caused increases in water yield. Coniferous forest has the highest influence on water yield, followed by deciduous hardwood and shrub. Komatsu et al. (2008) examined the changes in water yield during the course where deciduous forest was replaced by coniferous forest in a catchment in northern Japan. They found that the annual water yield increased when deciduous trees were felled, and that it decreased with the growth of coniferous trees. The study also showed that the difference in winter interception loss between deciduous forest and coniferous forest was the principal cause to the differences in water yield. Hence, it was inferred that the conversion of coniferous to deciduous forest can be used to increase water yield.

Although experimental comparisons in principle are straight forward, the land-use and hydrology of a catchment normally change rather slowly, and ideal paired catchments rarely exist. Hence, hydrological models have been used in order to explore the hydrological implications of different land uses (Elfert and Bormann, 2010). After setting up a model and estimating the most important parameters, the expected impact of alternative land-use scenarios on the water balance and dynamics can be quantified (Elfert and Bormann, 2010; Gustard and Wesselink, 1993; Niehoff et al., 2002; Wijesekara et al., 2012). Gustard and Wesselink (1993) established a lumped conceptual model for the Balquhidder catchment in the UK, and set different interception and transpiration rates for pasture, coniferous forest, heather, etc. They found that after afforestation with coniferous forest, the flow duration curves shifted down, the annual minimum discharge values decreased, the discharge reduced for a given frequency of occurrence, and the minimum storage to maintain a given water yield increased. In a study by Zhang and Hiscock (2010), the MODFLOW model with the FAO-EA recharge model revealed a reduction in recharge of up to 45% in the simulations with four land-use scenarios with different woodland coverage. They found that the reduction in recharge was more significant in winter than in summer.

With the implementation of the ambitious afforestation plan and the need for renewable energy sources, the structure and type of forest and coverage are changing in Denmark. It is therefore necessary to study the hydrological implications of the possible land-use changes. Recently, a SVAT code was integrated into the MIKE SHE modeling framework (Overgaard, 2005) making it possible to carry out physically based and spatially distributed modeling of evapotranspiration, groundwater recharge and integrated catchment responses like stream discharge in response of land use changes. By studying the potential groundwater response to the land-use change, it would offer a guideline for researchers and policy makers to better understand the relationship between land-use and groundwater balance, and hence better protect the environment.

Using the SVAT implementation in MIKE SHE (Overgaard, 2005) to obtain a physical based and distributed description of two catchments in Denmark, our primary objectives are 1) to test if additional water resources, especially groundwater resources, can be obtained by changing the current forest types from coniferous to broadleaves, 2) to test how the water resources are impacted if the area covered by forest, either broadleaves or conifers, is doubled and 3) to test how more extreme scenarios including forest only or agriculture only cases impacts the hydrological cycle.

The article is organized in four parts. 1) The first part describes the study areas including the Skjern River catchmet in the western part of Denmark and the Lejre area in the eastern part of Denmark. Alternative land use scenarios are presented. 2) The model setups for the two catchments are described and the performance under current land use is presented. 3) Results on groundwater and surface water for alternative land use scenarios are presented. 4) Finally, the results are discussed and the most important conclusions are presented.

2. Materials and methods

2.1 Study areas

The Skjern River is one of the largest rivers in Denmark (shown in Fig. 2.1). The river drains the central and western part of Jutland. The upstream 1098 km^2 Ahlergaarde catchment (referred to as the ‘Skjern catchment’ in this study) is used as one of two study areas in the current project.

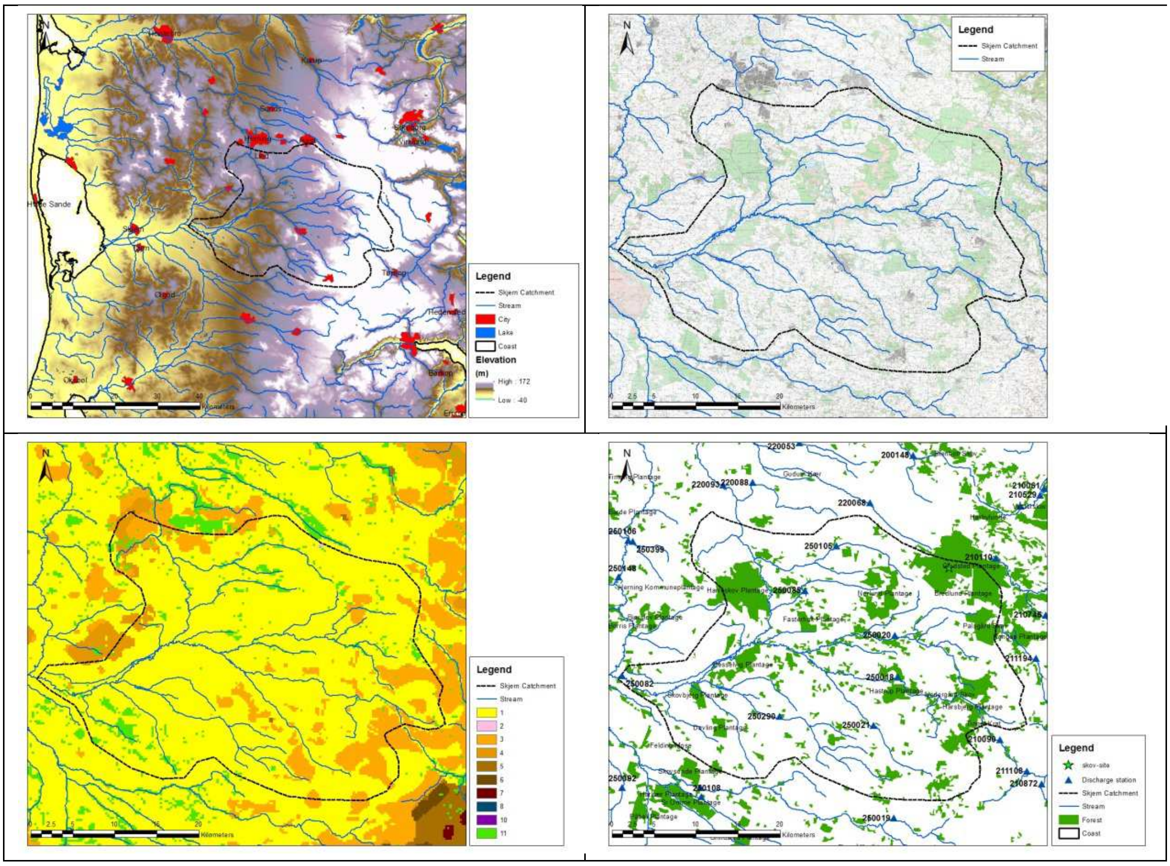


Figure 2.1 Upper left: Location and surface elevation of the Skjern River catchment. Upper right: Land use showing location of forest areas (green). Lower left: Soil type distribution (JB types). Lower right: Location of stream discharge stations.

The land surface elevation of the catchment decrease from approximately 130 m asl in east to about 10 m asl in west corresponding to an average gradient of 2.7 per mil. According to the Corine land-use map (EEA, 2006), the land-use of the Skjern catchment is dominated by agriculture (73.6%) and forest (17.4%), see Table 1. The agricultural crops have been categorized into the four most common crops (Mollerup, 2011), including different kinds of grasses (19%), winter wheat and barley (23%), spring barley (24%) and maize (7%). Conifer forest is the dominant forest type (16.5%) and the conifer plantations are primarily located at the north-eastern boundary of the catchment (Gludsted plantation) and at the north-western boundary of the catchment (Harreskov plantation), see Figure 2.1 (right panels). The surface geology (Figure 2.1, lower left) is dominated by glacial material from the Quaternary age, primarily characterized as outwash material, mainly from the Weichselian glaciation. The soil type is defined as coarse sandy soil, generally with high permeability. According to the soil type classes defined by Greve et al. (1997), sand and loamy sand dominates the top soil.

Table 1 Statistics on the land uses of the Skjern catchment (EEA, 2006). Pasture is counted as farmland as they are parameterized as crop in the modeling.

Land-use type	Area (km^2)	Fraction (%)
Agriculture	809	73.6
Heathland	20	1.8
Grassland	5	0.5
Conifer forest	181	16.5
Deciduous forest	2.5	0.2
Mixed forest	8	0.7
Urban	19	1.7
Other	49	4.8

The second study site (the Lejre area) is located in the central part of Zealand, in the eastern part of Denmark (Figure 2.2). The land surface elevation varies from 0 m above sea level (m asl) at the Køge Bay in the east and at Roskilde Fjord in the north to 120 m asl at the ridge in the western part of the model area, and to approximately 60 m asl at the northeastern boundary. The model area covers 465 km^2 with 88% consisting of land and the rest of sea. The focus area of the study is drained by the Langvad Stream valley system, see Figure 2.2.

Land use is dominated by agriculture (66.7%), urbanization (22%) and forest (9.3%). Most forest areas consist of mixed forest and it has been estimated that 53% of the forest consist of deciduous forest while 47% consist of conifer forest. Most forest is located at the south-western part of the model area (Figure 2.2, upper right). The surface geology is dominated by loamy soil types, see Figure 2.2 (lower left). In the area drained by Langvad stream, the top soils is primarily categorized as sandy loam while in the area closer to Køge Bay, loamy and sandy clay soil types dominates.

Table 2 Statistics on the land uses of the Lejre catchment (EEA, 2006). Pasture is counted as farmland as they are parameterized as crop in the modeling.

Land-use type	Area (km^2)	Fraction (%)
Agriculture	273	66.7
Conifer forest	18	4.4
Deciduous forest	20	4.9
Mixed forest	-	-
Urban	90	22
Other	8	2

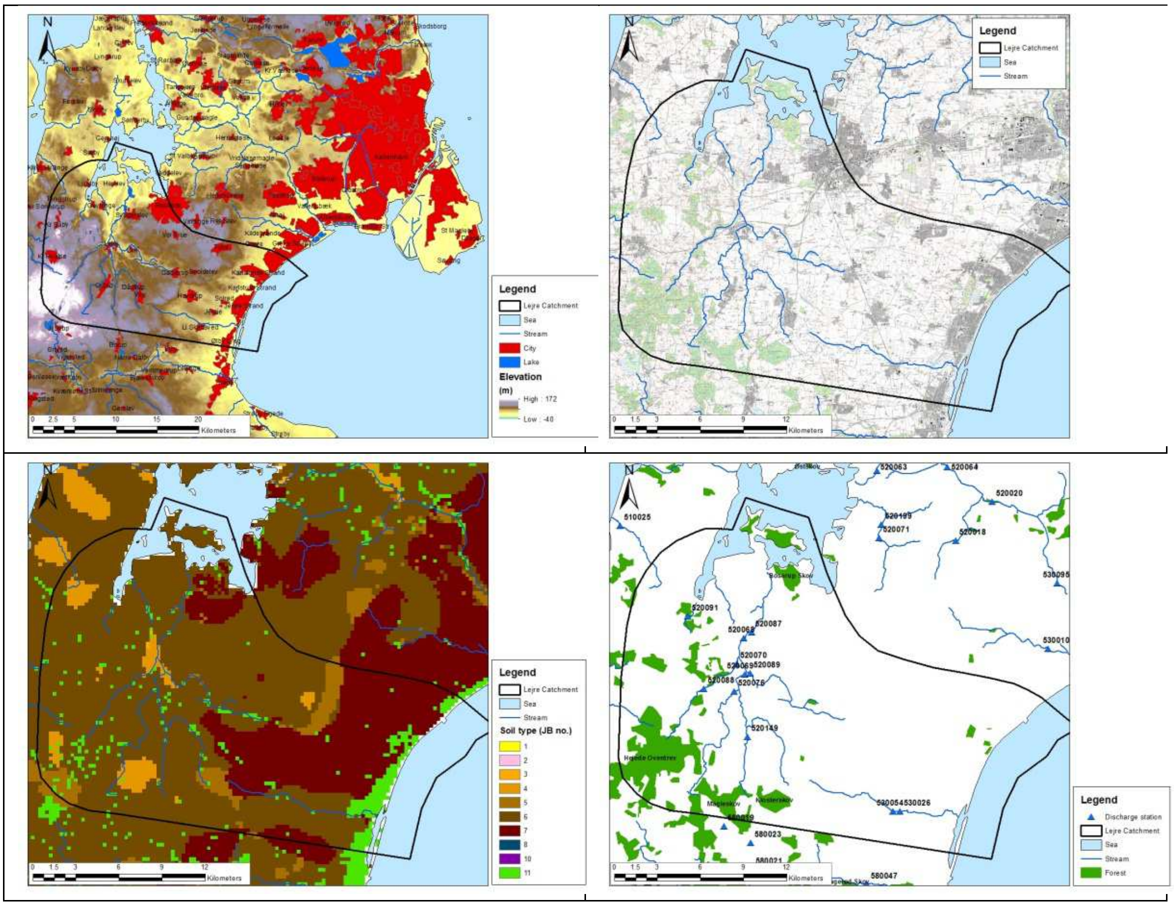


Figure 2.2 Upper left: Location and surface elevation of the Lejre catchment. Upper right: Land use showing location of forest areas (green). Lower left: Soil type distribution (JB types). Lower right: Location of stream discharge stations.

2.2 Climate data

Meteorological data from DMI have been used as input to the models. All the meteorological inputs (precipitation rate, air temperature, etc.) were available at an hourly time step. At the Lejre area only data on precipitation with hourly resolution from station 05805 Ishøj Varmeværk in the eastern part of the area has been used. Hence, the precipitation input to the hydrological model is homogeneous (see 3.2 Lejre catchment). In Figure 2.3 the average precipitation in the Skjern area is illustrated. A gradient in precipitation is observed with highest values in south and lowest values in north-east.

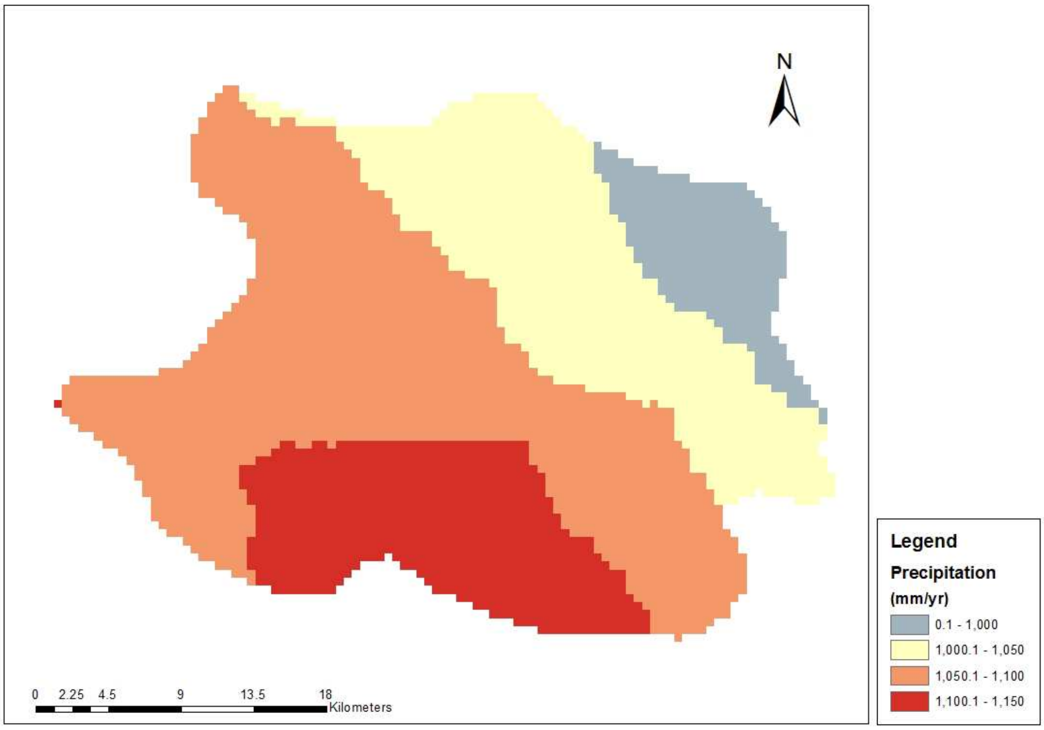


Figure 2.3 Average annual precipitation for the Skjern River catchment in the period 2001-2010.

2.3 MIKE SHE SVAT

The MIKE SHE SVAT model was adopted to simulate water balances in this study. It explicitly describes the water and energy balances between the soil, vegetation and atmosphere by coupling the hydrological processes of the sub-surface, the surface and the atmosphere (Overgaard, 2005). The SVAT model is based on the MIKE SHE model (Abbott et al., 1986; Graham and Butts, 2005), and replaces the simplified evapotranspiration (ET) module (based on potential ET) with a Soil-Vegetation-Atmosphere Transfer (SVAT) module.

The SVAT module is based on the model concept presented by Shuttleworth and Wallace (1985), an energy-based land surface model. It consists of a two layers system comprising the soil and vegetation canopy. The two-layer system model simulates a single, semi-transparent canopy layer located above the substrate such that the only way for heat and moisture to enter or leave the substrate layer is through the canopy layer. The fluxes of heat and water are driven by differences in temperature and humidity, respectively, and controlled by a number of resistances (Overgaard, 2005). At each time step of the model simulation, the SVAT model is fed with data on precipitation, net or global radiation, humidity, atmospheric pressure, temperature, and wind speed. Meanwhile, the SVAT produces output on latent heat flux and sensible heat flux. The modeling approach can be described by analogy to an electrical resistance system (Figure 2.4).

Figure 2.4 illustrates a leaf (green box) and water on soil and leaf surfaces (blue lines). Temperature and humidity at the wet (w) and dry (d) surfaces (l: leaf surface, s: soil surface, c: mean canopy level) are denoted T and e. The transport of latent heat (LE) and sensible heat (H) is illustrated on the left- and right-hand side of the figure, respectively. Rn is net radiation, and SH is soil heat flux (Overgaard, 2005).

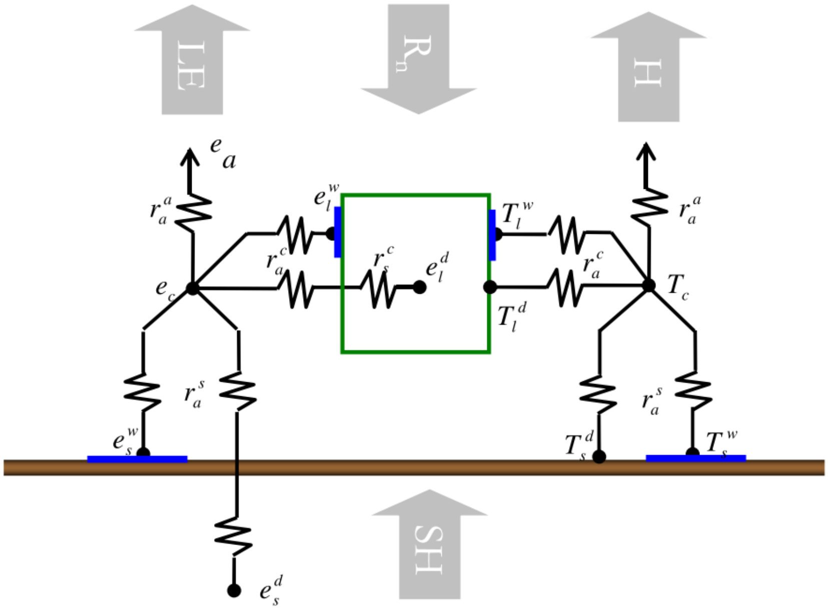


Figure 2.4 Structure of SVAT model described by analogy with an electrical resistance system. The green box represents leaves; the blue lines represent water on soil and leaf surfaces. Temperature and humidity at the wet (w) and dry (d) surfaces (l: leaf surface, s: soil surface, c: canopy level) are denoted T and e. Rn denotes net radiation and SH denotes soil heat flux. The transport of latent heat (LE) and sensible heat (H) is on the left-hand and right-hand side of the figure (Overgaard, 2005).

The resistances are denoted r and control the flux of energy and vapor. The aerodynamic resistance, r_a^a, controls all fluxes. Transpiration (E_t) from the canopy is additionally controlled by the stomata resistance, r_s^c, and the leaf boundary layer resistance, r_a^c. Interception loss, E_i, is controlled by the leaf boundary layer resistance, r_a^c. Soil evaporation, E_s, is a function of the soil evaporation resistance, r_g (not shown on Fig. 2.7), which increases as the top soil dries out, and the soil surface – canopy resistance, r_a^s. Finally, evaporation from wet soils is a function of the soil surface – canopy resistance, r_a^s.

Soil and vegetation parameters required by the SVAT module include (excluding soil hydraulic properties): leaf area index (LAI), interception coefficient (C_{int}), minimum stomata resistance (RSC_{min}), extinction coefficient (K_{ext}), average leaf width (w), vegetation height (h_{veg}), soil surface roughness (z_{0s}), albedo (α), root depth (z_{rd}), and root mass distribution (A_{root}). A detailed description of these parameters and how they were estimated can be found in Sonnenborg et al. (2014). The parameter estimates are summarized below.

2.4 Parameterization

The actual value of many of the vegetation parameters of the SVAT model is not known a priori. However, the temporal developments in LAI and vegetation height were prescribed as known. In Fig. 2.5 the annual variation of LAI and vegetation height is shown for spruce, beech and willow. Vegetation heights for spruce and beech have been specified to a constant value of 17.5 m. For willow, the vegetation is assumed to grow in three year cycles where they are cut at the end of the cycle. The height of the vegetation is assumed to increase steadily from 1 m to 4 m during the period. LAI is specified as constant for spruce. The beech is assumed to come into leaf at May 1 and the maximum LAI is reached within a month. The LAI decrease moderately from beginning of September and the LAI reach its minimum level at the end of October. The willow is assumed to come into leaf in the beginning of April and to have a minimum LAI at the end of November. The maximum level of LAI increases during the three year growing cycle from 4 to 6.

In Fig. 2.6 the development in LAI and vegetation height for the agricultural crops are illustrated. Grass has a relatively high vegetation height and LAI all through the year whereas spring barley and maize only are active during summer. Spring barley has a relatively short growing season, from beginning of May to beginning of August, while the growing season of maize is relatively late, from end of June to harvest in beginning of October. The fields where spring barley and maize are grown are assumed to be without crops between harvest and spring. This period is represented by small values of LAI and vegetation height corresponding to a litter layer or low vegetation.

In Table 3, vegetation parameters needed for the SVAT model for all the different plant types considered are listed. The parameterization of beech and spruce is based on automatic model calibration against measurements of soil water content, throughfall and actual evapotranspiration. For the remaining vegetation types literature values are used (see Sonnenborg et al., 2014).

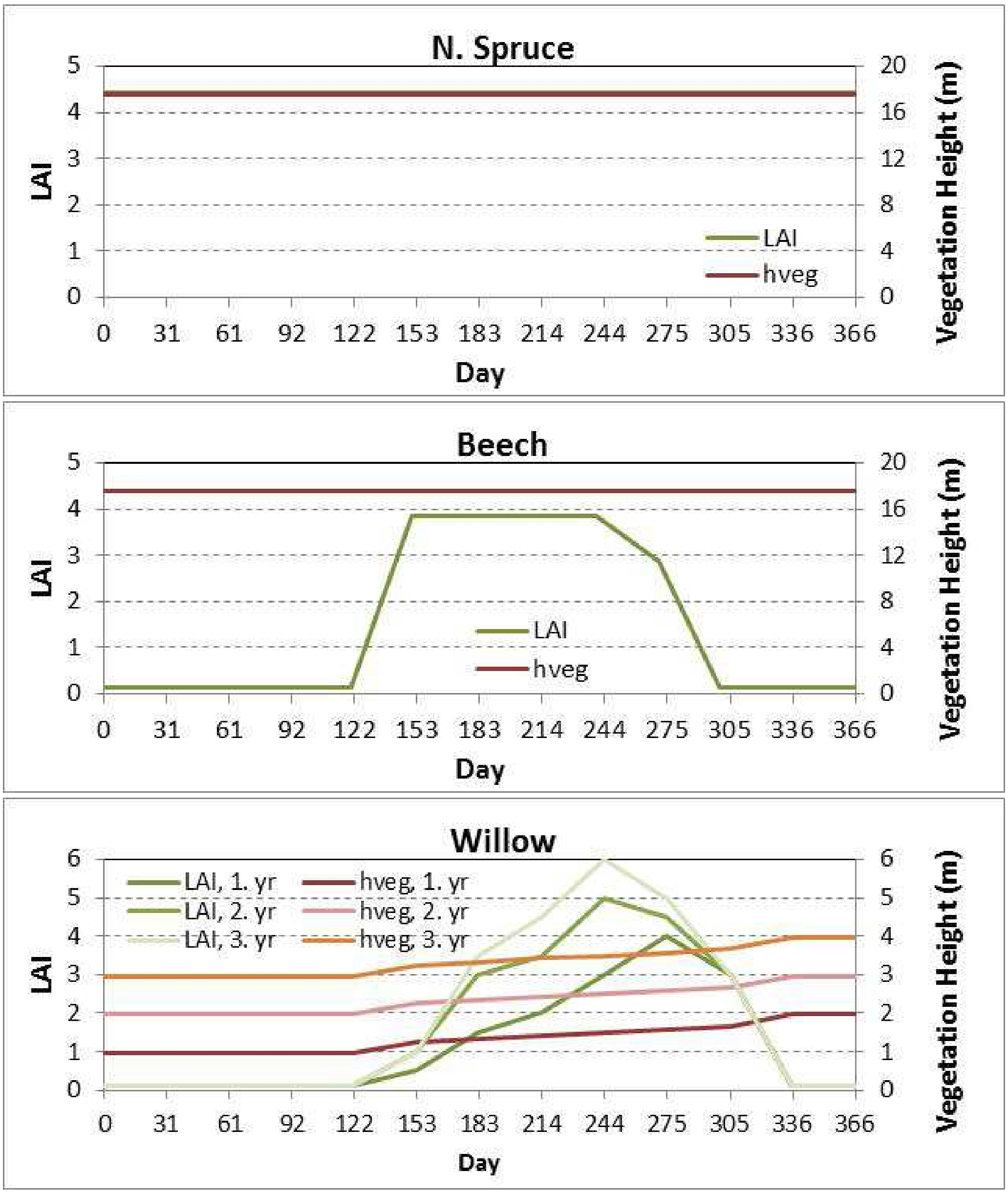


Figure 2.5 Temporal development in leaf area index (LAI) and vegetation height for spruce, beech and willow.

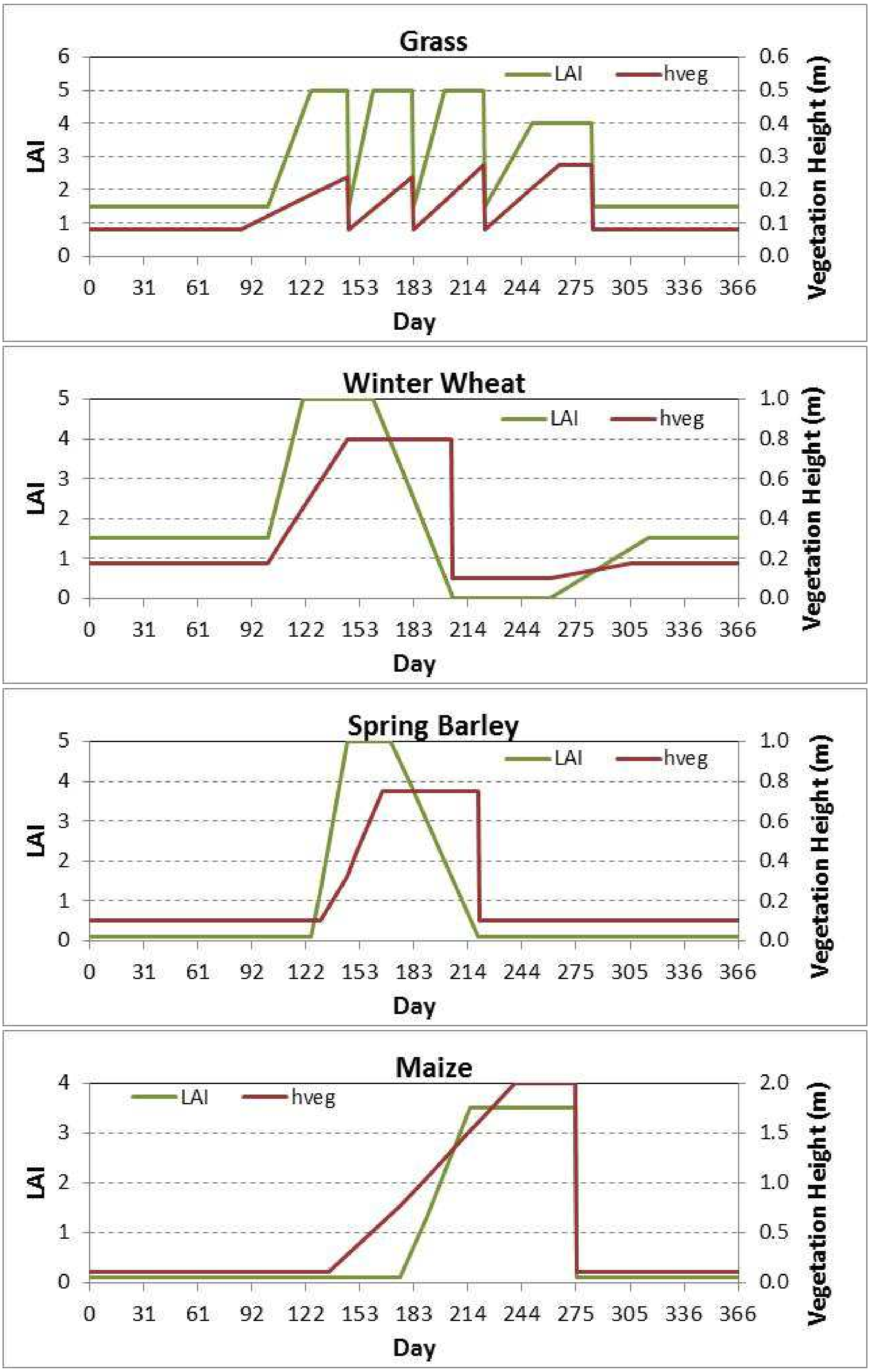


Figure 2.6 Temporal development in leaf area index (LAI) and vegetation height for agricultural crops, grass, winter wheat, spring barley and maize.

Table 3 Vegetation parameters for different forest types and crops. Root depths for different soil types are listed. From Sonnenborg et al. (2013).

	Spruce	Beech	Willow	Grass	W. Wheat	S. Barley	Maize
Albedo, α (-)	0.08	0.18	0.2*	0.185*	0.195*	0.19*	0.18*
Veg. height, h_{veg} (m)	17.5	17.5	3.96*	0.275*	0.8*	0.75*	2.0*
LAI (m^2 m^{-2})	4.44	3.15*	6.0*	5.0*	5.0*	5.0*	3.5*
C_{int} (mm LAI^{-1})	0.29	0.14	0.2	0.05	0.05	0.05	0.05
RSC_{min} (s m^{-1})	230	100	30	110	110	110	110
Leaf width, w (m)	0.022	0.025	0.01	0.02	0.02	0.02	0.02
Ext. coeff., K_{ext} (-)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
z_{0s} (m)	0.03	0.03	0.03	0.03	0.03	0.03	0.03
A_{root} (m^{-1})	1.05	2.50	2	0.25	0.25	0.25	0.25
Root depth, JB1 (m)	1.00	1.50	1.2*	0.5*	0.5*	0.5*	0.5*
Root depth, JB4 (m)	1.00	1.50	1.2*	0.6*	0.9*	0.85*	0.85*
Root depth, JB6 (m)	1.00	1.50	1.2*	0.6*	1.2*	0.9*	1.0*

* Value varies over season. Maximum value listed.

2.5 Land use scenarios

A multi-criteria evaluation (MCE) method was developed to enable GIS-aided land-use planning (Pang, 2013). Based on spatially distributed information on soil type, land use type, depth to groundwater table and the vertical component of groundwater flow at shallow depths, each location was evaluated according to a user defined numerical rating scale (from -100 to +100) corresponding to unsuitable and suitable locations, respectively. The four ratings were subsequently superimposed using a weighted linear summation into a layer of holistic scores and used to generate different land-use scenarios in a customized GIS program. The method was designed such that it was possible to constrain the allocation of land use to specific areas. Hence, the method made is possible to automatically find the optimal land use distribution according to the four criteria listed above and at the same time to keep the present land use in specific areas, e.g., urban areas.

The four criteria were selected based on the following arguments. The soil type of the root zone is an important factor for farming, and the most profitable soil types were therefore reserved for farming (e.g., loamy sand was considered better for farming in the Skjern River catchment than the sandy soil type). Nine land use types were defined (agriculture, deciduous forest, conifer forest, mixed forest, shrub, wetlands, water bodies and urban) and depending on the scenario each land use were given a score to rank which land use to change first. Both groundwater depth and flow direction were extracted from the national water resources model (Henriksen et al., 2003), where the flow direction was found as the vertical component of the flow between the two uppermost numerical layers representing the groundwater zone. Hence, upward flow corresponds to a discharge area where groundwater flows to surface waters (normally to streams), while downward flow corresponds to recharge areas where groundwater is generated to the deeper aquifers (normally far from major streams). The most optimal locations for generating additional groundwater were considered to be areas with deep groundwater and downward flux. A more detailed description of the MCE method can be found in Pang (2013).

A number of land use scenarios have been defined where the area and type of forest have been changed, see Table 4 and Figures 2.7 - 2.10. The reference situation is defined by the present land use (scenario P1). Three scenarios have been defined with beech and with spruce, respectively. In the first cases (B1 and S1) the current forest area has been changed such that all forest is either beech (B1) or spruce (S1). In the Skjern River catchment, scenario S1 (Figure 2.7) is almost identical to scenario P1, as the forest is dominated by spruce under current conditions. Scenario B1 is designed to analyze the potential for generating more groundwater by changing the current forest type from conifer (spruce) to deciduous (beech) forest.

In scenarios S2 and B2 the area with forest is doubled. Hence, in scenario B2 the forest area covers twice as much as in the current situation and all forest is defined as beech. S2 is similar to B2, except that the forest type is changed to spruce. The MCE algorithm has been parameterized such that locations with deep groundwater and downward flowing groundwater are preferred for new forest location. Finally, in scenario B3 and S3 the entire area (except cities and lakes) is covered by forest and represents an extreme situation (or the situation before the forest was removed by man).

Table 8 Land use scenarios implemented at Skjern and Lejre catchments.

Scenario	Forest type	Area covered by Forest	Priorities for forest location
P1	Mixed	Present	-
B1	Beech	Present	-
B2	Beech	Double	Deep GWT
B3	Beech	Full coverage	Preserve urban
S1	Spruce	Present	-
S2	Spruce	Double	Deep GWT
S3	Spruce	Full coverage	Preserve urban
W1	Willow+Mixed	Double	Shallow GWT
A1	Agriculture	None	-

Two additional scenarios are analyzed. In scenario W1 (Figure 2.8) the forest area is doubled by planting willow in areas with shallow groundwater and upward flowing groundwater. Hence, the willow is primarily located in stream valleys. In scenario A1 all forest have been removed and replaced by agriculture. It is assumed that the distribution between grass, winter wheat, spring barley and maize is the same as used in the remaining area. For the current land use scenario (P1) in the Lejre catchment the exact distribution of broadleaf and conifer forest within the forest area was not mapped in digitalized form, but from forest statistics they were estimated to cover 53% and 47% of the forest area. An inspection of forest district maps revealed a complex mosaic between the two forest types. Hence, we thus simply used a random distribution of the two forest type (53 vs 47%) on the forest pixels in the catchment.

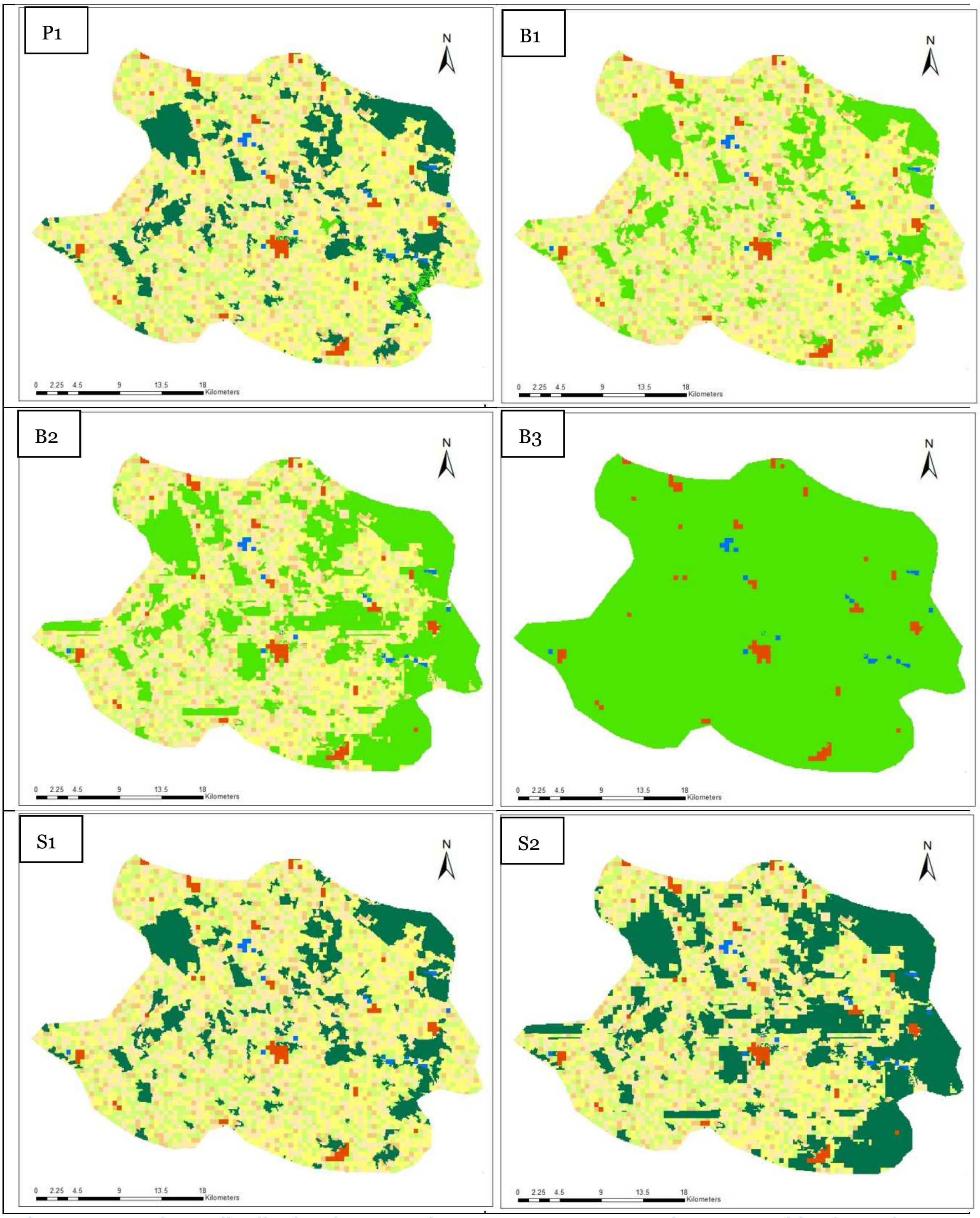


Figure 2.7 Land use distribution for scenario P1, B1, B2, B3, S1, and S2. Legend is shown in next figure.

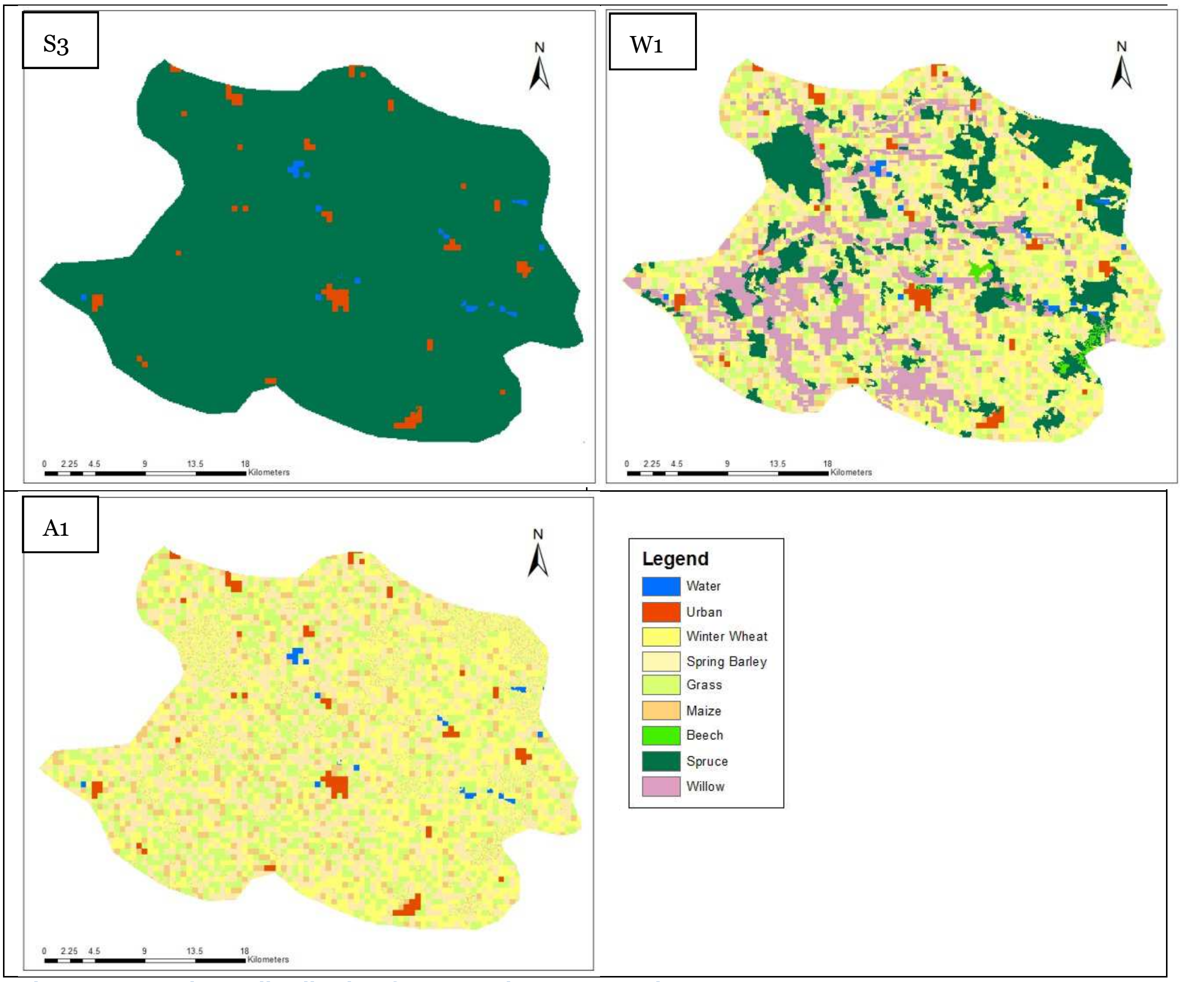


Figure 2.8 Land use distribution for scenario S3, W1 and A1.

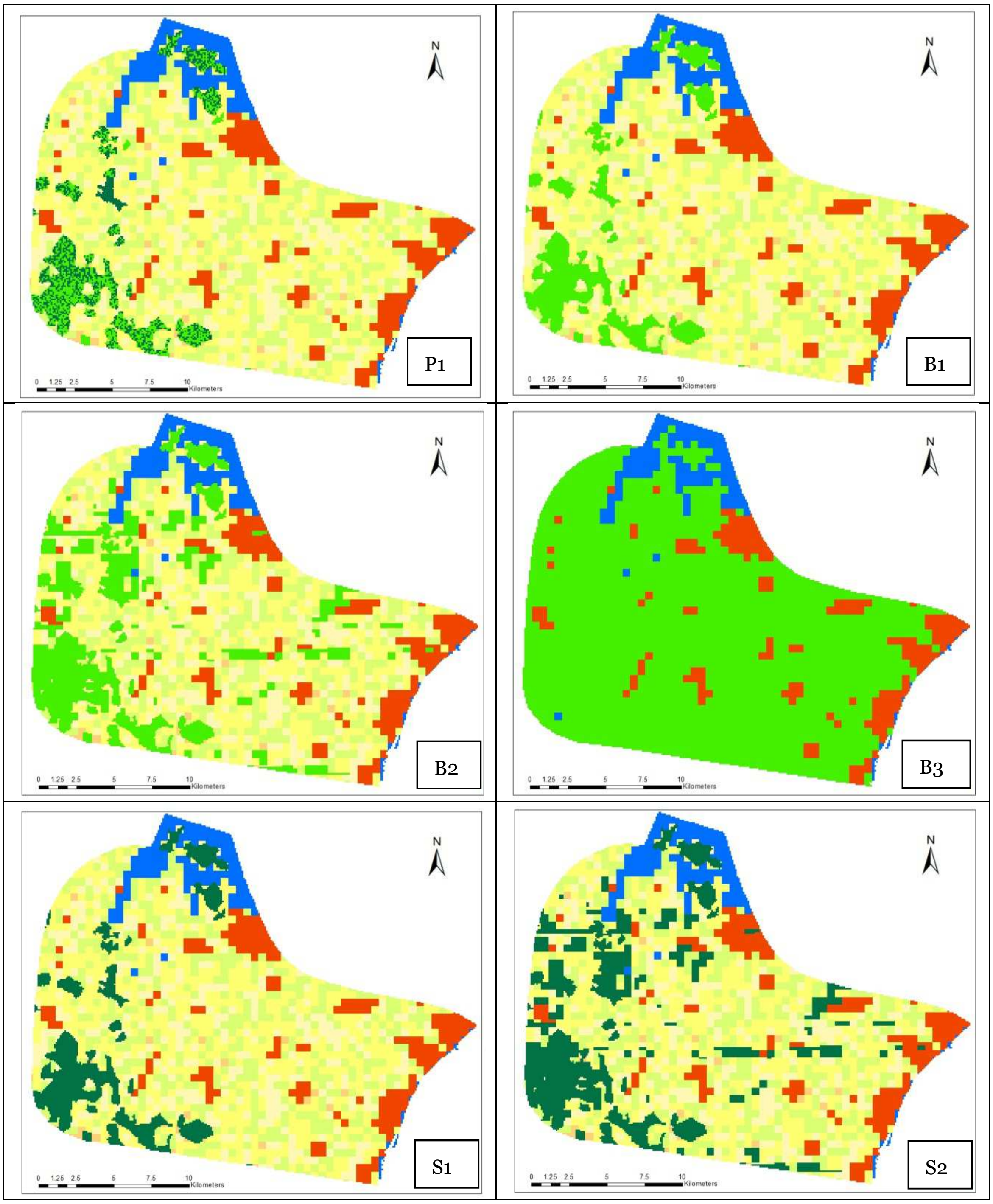


Figure 2.9 Land use distribution for scenario P1, B1, B2, B3, S1, and S2. Legend is shown in next figure.

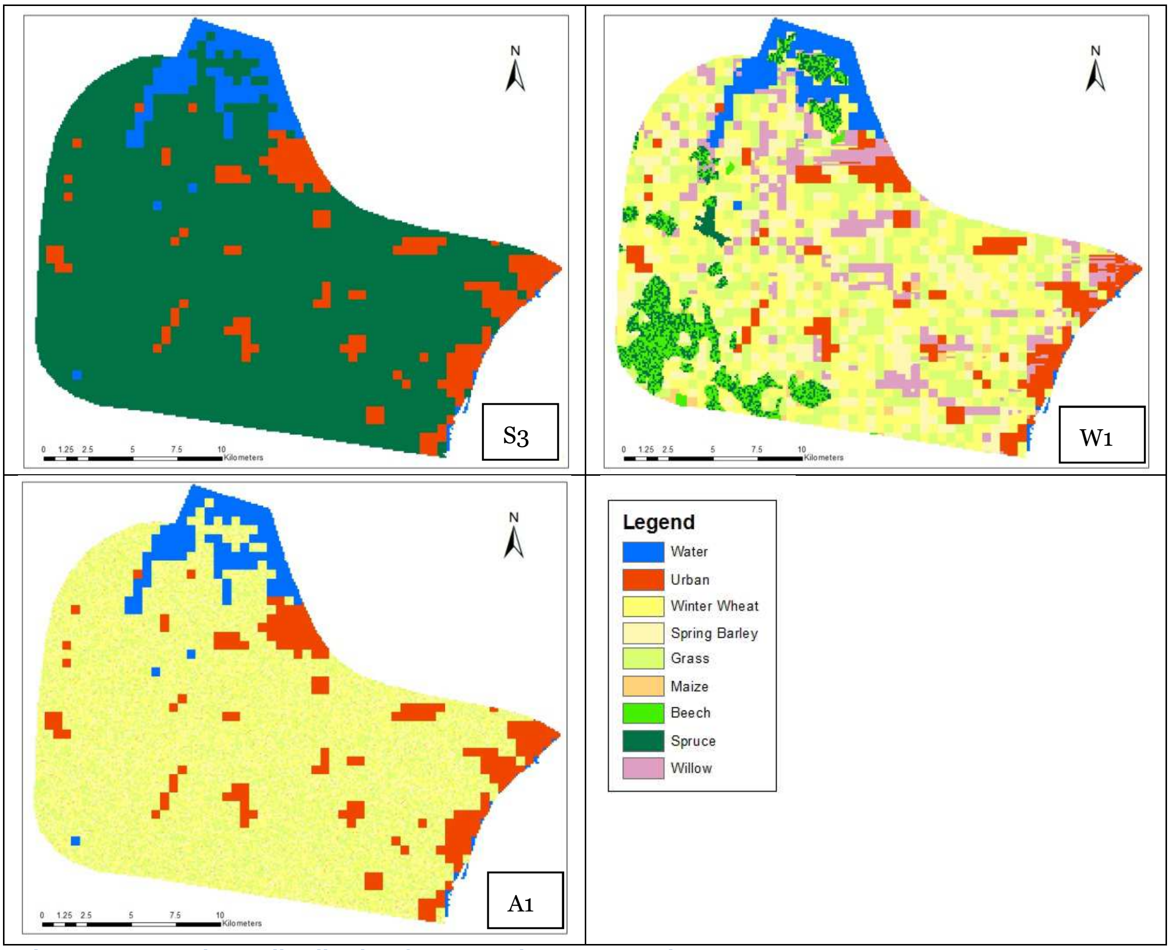


Figure 2.10 Land use distribution for scenario S3, W1 and A1.

3. Validation of the hydrological model

3.1 Skjern River catchment

The distributed MIKE SHE SVAT model for the Skjern area is based on a model set up by Stisen et al. (2011) which covered the entire 2500 km^2 Skjern River catchment using a 500 m horizontal discretization. The forcing data for precipitation were given as krieged fields at 2 km resolution, which were based on daily observations from rain gauge stations within and around the Skjern catchment. Other distributed climatic inputs all have an hourly resolution, e.g. air temperature, humidity, shortwave radiation, wind speed, and air pressure. In the model of Stisen et al. (2011) land surface parameters such as LAI and albedo are estimated from remote sensing data. Following a sensitivity analysis based on observations of discharge and groundwater levels, automatic model calibration were carried out.

The calibrated MIKE SHE SVAT model from Stisen et al. (2011) was subject to a number of changes in the current study. Daily precipitation data was replaced by hourly data, as fine time step resolution was found to be important for modeling of interception loss (Sonnenborg et al. 2014). Another change was on the land use module of the SVAT model. The original remote sensing-based input was replaced by land use maps and properties (i.e. the maps in Fig. 2.7-8). The scenario representing present land use conditions (P1) was created as a combination of the location of deciduous forests and coniferous forests derived from the Corine map (EEA, 2006) while the location of other land uses and corresponding parameters were transferred from a SVAT model set up by Mollerup (2011).

The high resolution precipitation input to the model resulted in overestimation of the peak discharge. Hence, the parameters that are most sensitive to the peak discharge were calibrated using Autocal (DHI, 2011). The following parameters were adjusted: the detention storage, which controls how high the water level should be before overland flow takes place, was increased from 6 mm to 20 mm; the drainage depth was increased from 0.50 m to 0.99 m, the drainage time constant was increased from 9.67×10^{-8} s^{-1} to 7.18×10^{-7} s^{-1}; and the van Genuchten parameter n of the sandy soil was decreased from 1.32 to 1.29. The resulting simulation of stream discharge at station 250082 (Ahlergaarde station) is shown in Figure 3.1. The model provides a fair description of both high and low flows with a Nash–Sutcliffe coefficient of 0.67. In Figure 3.2 flow duration curves at the upstream station 250020 and the downstream station 250082 are illustrated. At the upstream station (250020) the model captures the observed curve satisfactorily, however, with some deviation at high exceedance probabilities, whereas for the downstream station (250082) the model performs best at high and low exceedance probabilities but has some problems to reproduce the flows near the median values. However, the model is found to reproduce the dynamics of the system well enough to be used as the basis for a scenario analysis.

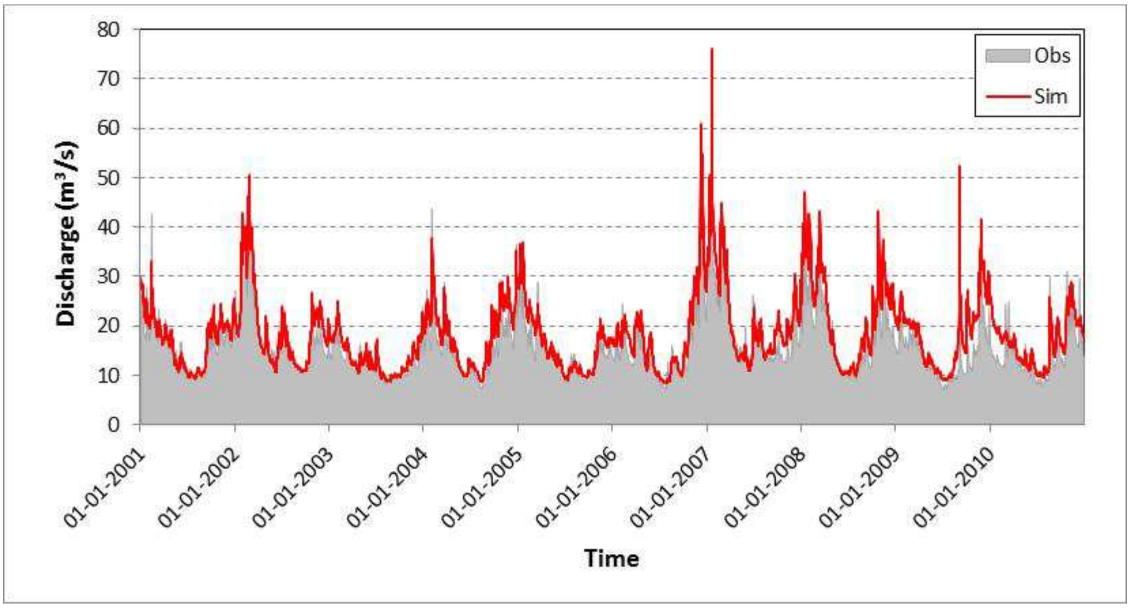


Figure 3.1 Observed and simulated hydrograph at discharge station 250082 at the outlet of the Skjern River catchment. R^2 = 0.67.

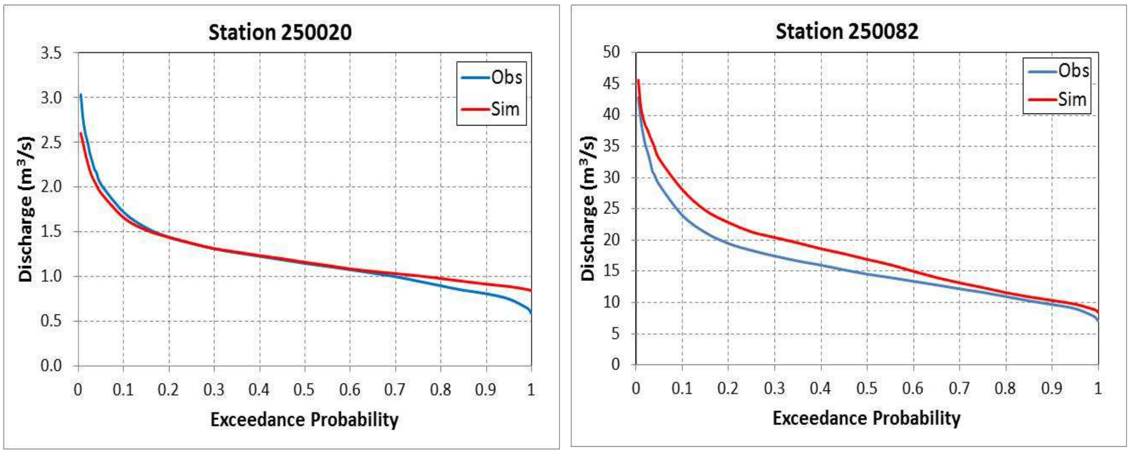


Figure 3.2 Observed and simulated flow duration curves at discharge station 250020 (upstream) and 250082 (downstream).

3.2 Lejre catchment

The model setup for the Lejre catchment is based on a model by Seifert et al. (2012), wherein the setup is referred to as model N2. The hydrological model is constructed using the MIKE SHE/MIKE 11 modeling software including the modules for evapotranspiration, overland flow, land use, a two-layer description of the unsaturated zone, saturated zone, drains, and pumping wells. The model covers an area of 465 km^2. A uniform cell size of 200 m was used. The model was calibrated by inverse optimization using PEST (Doherty, 2004, 2008) against observations of hydraulic head and stream discharge for the period 2000– 2005. Subsequently, the model was validated against observations from the period 1995–1999, where groundwater abstraction is decreasing and both wet and dry years are found.

In the current study time series with daily values of precipitation (10 km grid) was replaced by hourly precipitation based on data from station 05805 Ishøj Varmeværk. Unfortunately, data with hourly resolution was not available from other stations in the area covering the catchment and the precipitation input was therefore based on station 05805 only. Additionally, the description of the unsaturated zone, land use and evapotranspiration were replaced by the model of Mollerup (2011).

In Figure 3.3 the observed and simulated discharge at station 520082 located at the downstream end of the Langvad stream catchment is shown. The model has difficulties to capture some of the peak flows. However, as the precipitation input to the model is based on only one station, significant deviations may be expected. The flow duration curve for this station, Figure 3.4 (to the right), reveals that the model provides a fair description of the discharge variations. The model has, however, problems to reproduce the flow duration curve at the upstream station 520088 at low and high exceedance probabilities. However, the median response is reproduced reasonable.

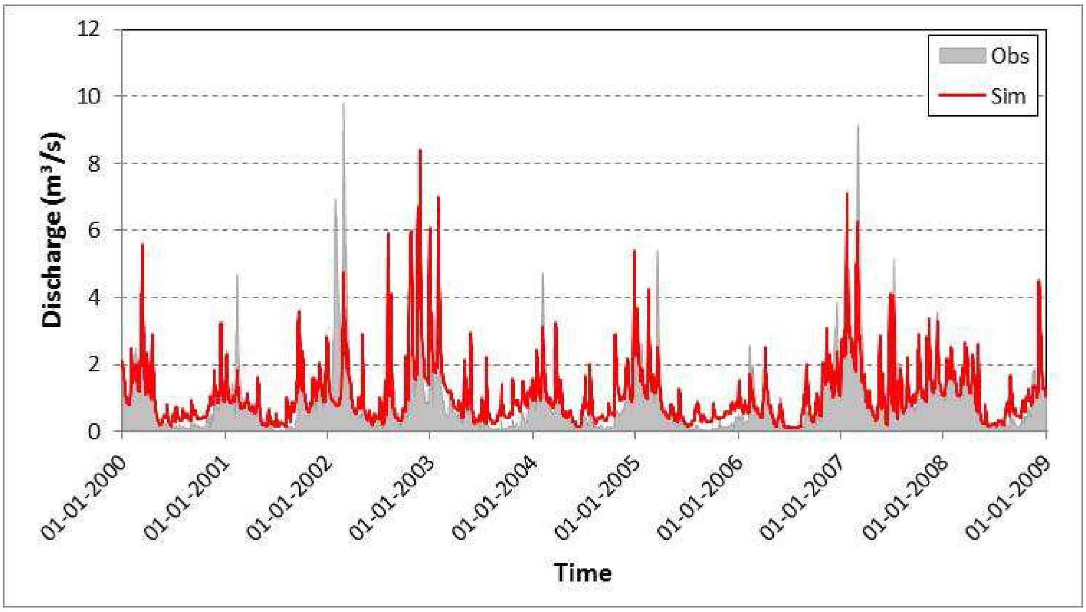


Figure 3.3 Observed and simulated hydrograph at discharge station 520068 at the outlet of the Langvad River catchment. R^2 = 0.49.

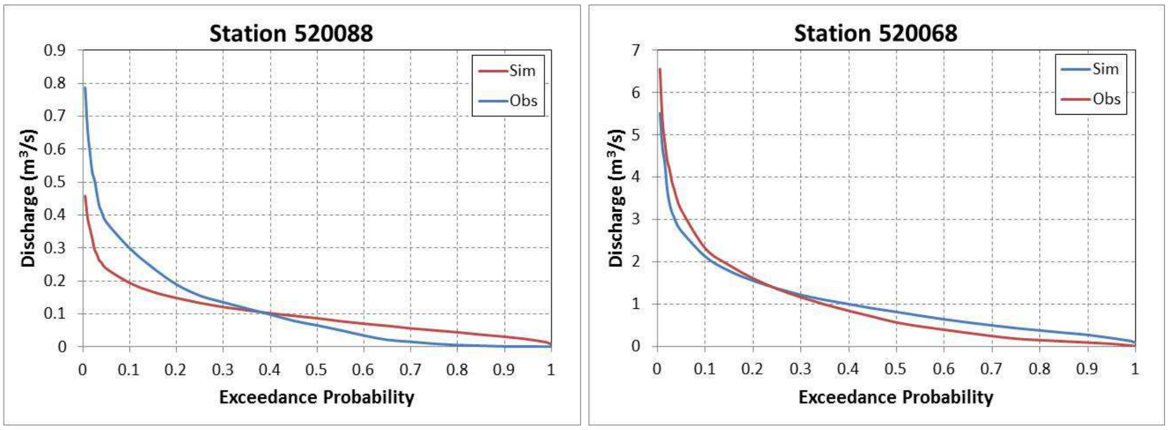


Figure 3.4 Observed and simulated flow duration curves at discharge station 520088 (upstream) and 520068 (downstream).

The calibrated catchment models where run with a 10-year set of hourly climate data (period) for each scenario first as a 'warm up' to get an equilibrium with the new land use. Subsequently, the same 10-year simulation was repeated and results for the land use impact was extracted from this second run. For the Lejre catchment the 'warm up' was increased to 20-years, since longer time was needed to approach equilibrium with the new land use on loamy soils.

4. Impact of land use changes

4.1 Skjern river catchment – from spruce to beech

First, results on evapotranspiration representing the present land use distribution (P1) is presented and subsequently compared to the case where spruce has been replaced by beech. In Figure 4.1 the total annual evapotranspiration (ET) for the Skjern River catchment is presented. Additionally, the total ET is split up into the three major components, transpiration, soil evaporation and interception loss. The total ET (upper left panel) varies according to water availability and land use, where higher ET is found at places with shallow groundwater and/or forest plantations. Interception loss (upper right panel) is high, in the order of 300 mm/yr, for the areas with spruce compared to the agricultural areas, where interception loss generally is less than 100 mm/yr. The magnitude of interception loss is partly controlled by the amount of precipitation, which is higher towards south than north-east, see Figure 2.3.

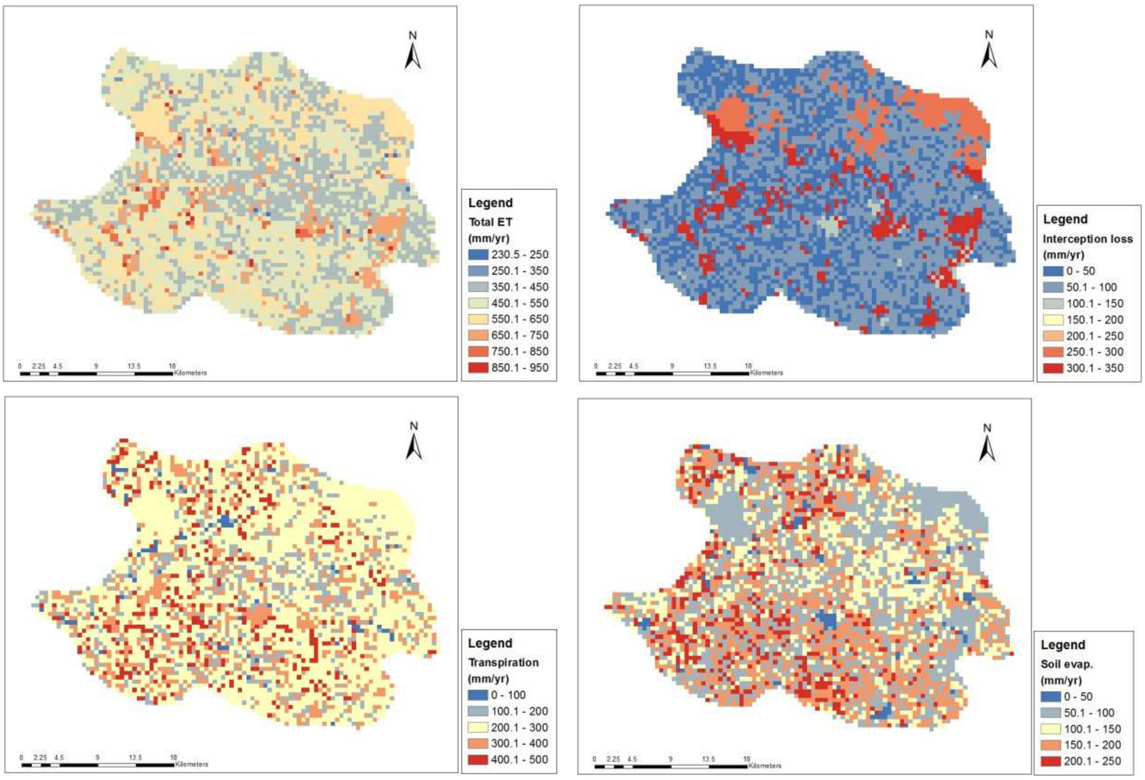


Figure 4.1 Evapotranspiration components for the Skjern River catchment with land use scenario P1. Upper left: Total evapotranspiration. Upper right: Interception loss. Lower left: Transpiration. Lower right: Soil evaporation.

Transpiration (lower left) is primarily controlled by the depth to the groundwater table, where transpiration rates above 400 mm/yr are found in stream valleys and other areas with shallow groundwater, while much lower transpiration is found where the depth to the groundwater table is more than 2 – 3 m. Soil evaporation is partly controlled by the amount of energy reaching the ground surface. Hence, relatively low soil evaporation is found in the areas covered by spruce. Here, LAI is high during the entire year and a relatively small amount of energy penetrates the canopy. Additionally, a high fraction of the available energy is used for interception evaporation. At the agricultural areas the soil is not covered by plants after harvest and therefore exposed directly to the incoming shortwave radiation resulting in relatively high soil evaporation. The largest total ET is found in forest areas, partly due to the high interception loss, partly due to the lower albedo of the spruce (see Table 3) and therefore higher amount of available energy.

In Figure 4.2 similar results from scenario B1, where all spruce have been replaced by beech, are presented. The total evapotranspiration for this scenario shows no clear impact on the forest location. Compared to scenario P1 the interception loss of the forest is significantly reduced with values not exceeding 150 mm/yr. The transpiration and the soil evaporation responses are quite similar to those found in P1.

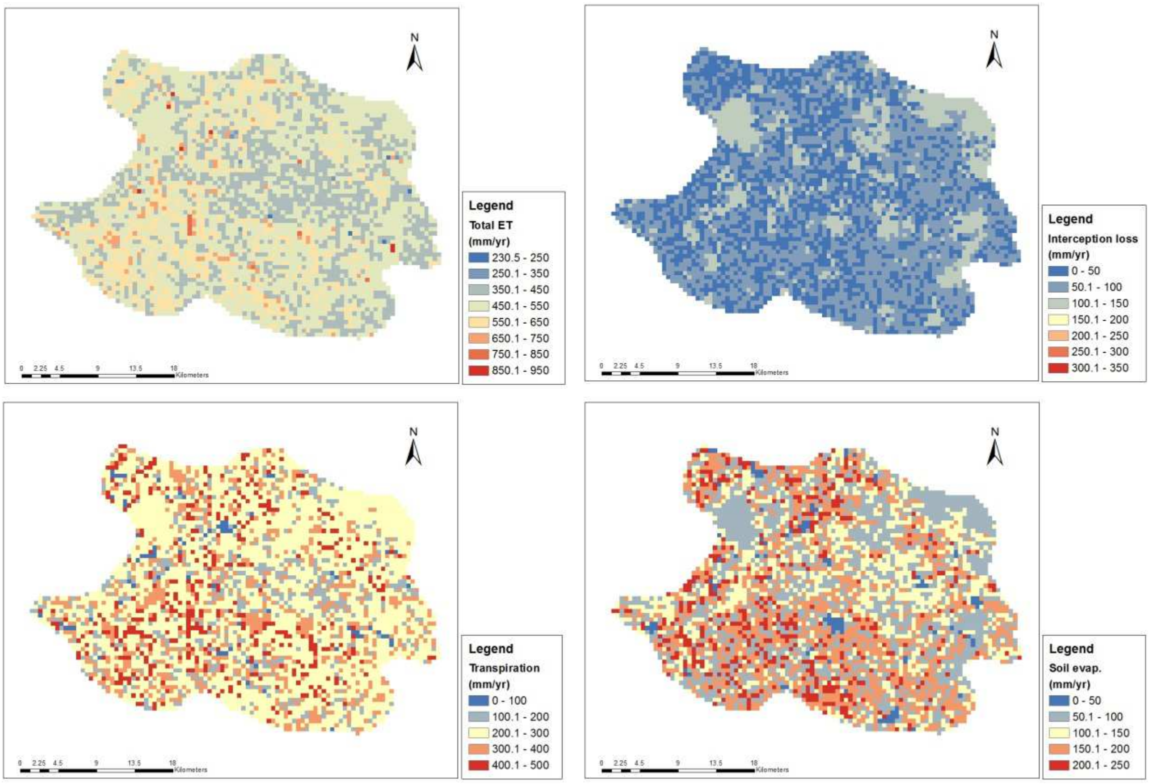


Figure 4.2 Evapotranspiration components for the Skjern River catchment with land use scenario B1. Upper left: Total evapotranspiration. Upper right: Interception loss. Lower left: Transpiration. Lower right: Soil evaporation.

Since total evapotranspiration in the forest area decrease when spruce is replaced by beech, the groundwater recharge is expected to increase. This is shown in Figure 4.3 (left) where the difference between scenarios B1 and P1 with respect to the net exchange between the unsaturated and the saturated zones are illustrated. Blue colors (negative values) indicate higher groundwater recharge while red colors indicate a decrease. In all areas where spruce has been substituted by beech an increase in groundwater recharge is observed. The recharge in areas with forest increases by approximately 150 mm/yr, while the changes in the remaining area are insignificant.

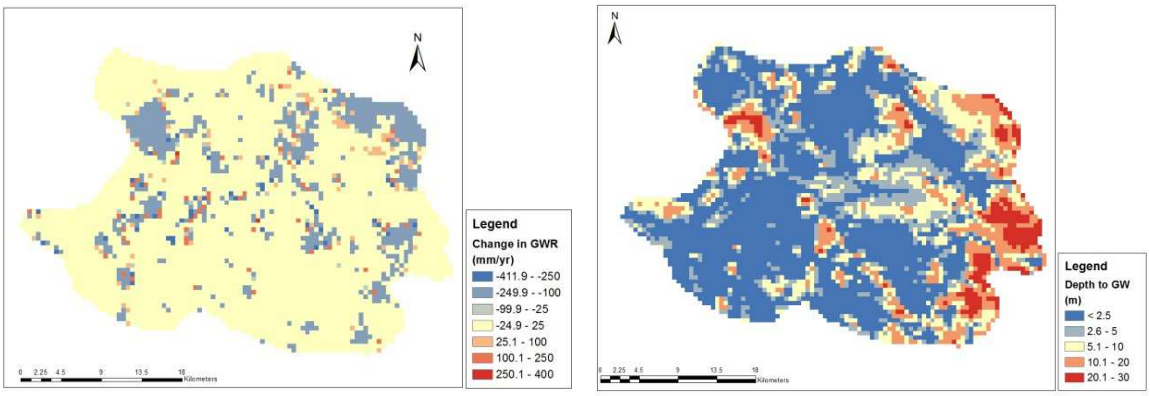


Figure 4.3 Changes (i.e. P1 minus B1) in net groundwater recharge to the groundwater table (left) and depth to the groundwater table (right) for scenario B1.

The changes in groundwater recharge have a pronounced effect on the groundwater heads in the area. In Figure 4.4 the difference in hydraulic head is shown for the shallow groundwater (left) and the primary groundwater reservoir (right). Significant increases of up to three meters are found in the eastern part of the model area where spruce has been replaced by beech. The response is quite fragmented in upper aquifer, where the effect of the increase in recharge at a specific location is clearly recognized. A more smoothened response is observed in the primary aquifer (Figure 4.4, right). Here, the hydraulic head is predicted to increase by more than two meters at the north-eastern boundary and in a large part of the catchment the head increases by more than 10 cm.

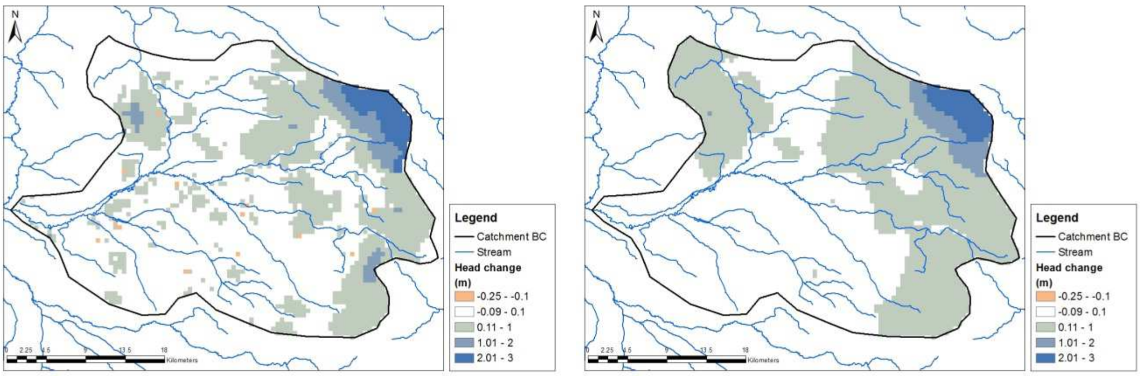


Figure 4.4 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario B1. Right panel: Results for primary deep groundwater aquifer for scenario B1.

The effect of the land use change with respect to stream discharge is shown in Figure 4.5. Here, the flow duration curves for a discharge station with a relatively small catchment, st. 250020, and one with a large catchment, st. 250082, are shown (see Figure 2.1 for locations). St. 250020 is located immediately downstream of the large forest plantations in the eastern area, while st. 250082 is located at the outlet of the catchment and integrates the response of the entire catchment. In Figure 4.5 results for scenario P1 is hidden behind scenario S1 as the land use of the two scenarios is similar and the results therefore comparable. Comparing P1 and B1 at st. 250020 ('forest stream') reveals that the discharge increases at all exceedance probabilities. The median discharge (exceedance probability of 0.5) increases from 1.16 m^3/s to 1.26 m^3/s, corresponding to an 8% increase. The corresponding increase for exceedance probabilities of 0.1 and 0.9 are 10% and 5%, respectively. Hence, the relative impact is largest for the high flows. At the catchment outlet (st. 250082) the discharge increase by 3%-4% at exceedance probabilities of 0.1-0.9.

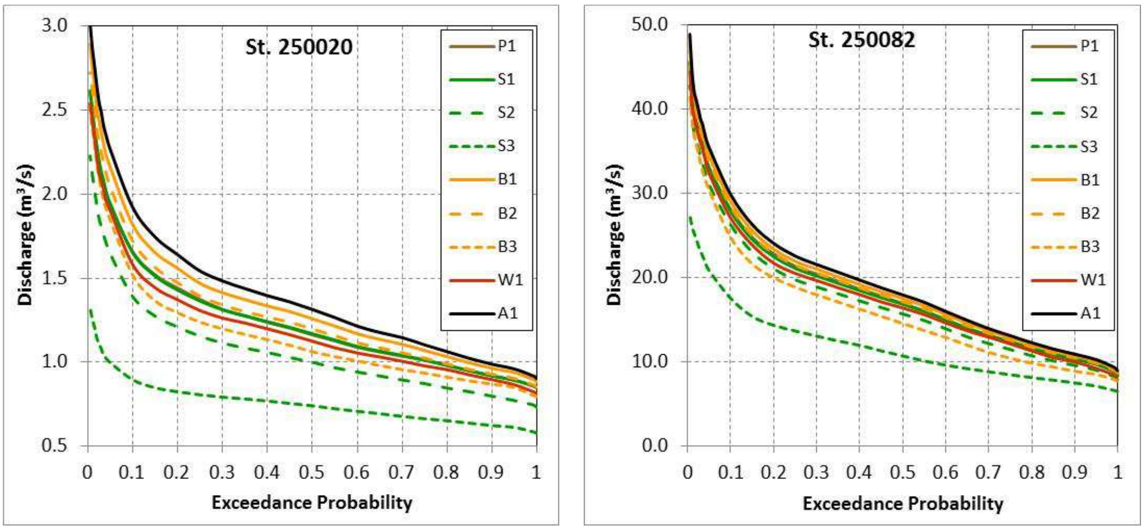


Figure 4.5 Exceedance probability at discharge station no. 250020 (left) and no. 250082 (right) for the defined land use scenarios. At both stations the line representing scenario P1 is hidden below scenario S1.

The median minimum value at st. 250020 (‘forest stream’), Figure 4.6, increases by approximately 4%. At st. 250082 the impact is slightly smaller, with an increase of about 3%.

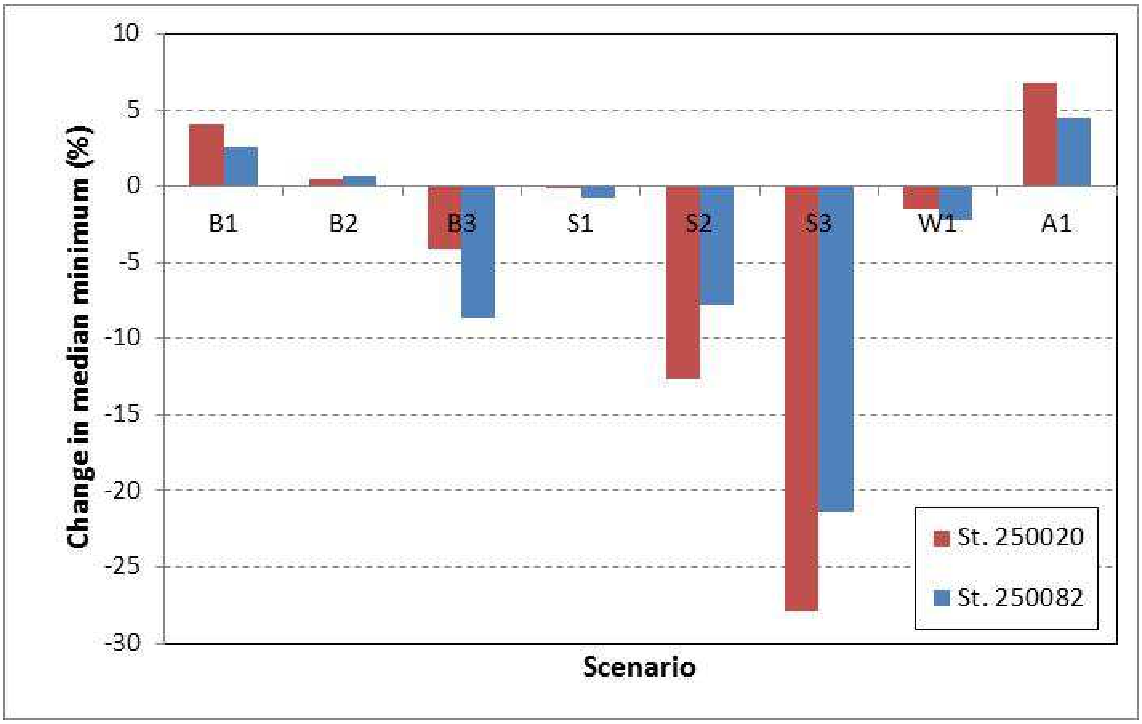


Figure 4.6 Change in median minimum at station no. 250020 (‘forest stream’) and no. 250082 (outlet) compared to the reference scenario (P1).

4.2 Skjern - Increasing area with forest

When the area covered by forest (beech) is increased and substitutes agricultural crops, the evapotranspiration increase and the groundwater recharge decrease. In Figure 4.7 the changes in recharge for scenario B2 (area with beech doubled) and B3 (whole area covered by beech) are illustrated.

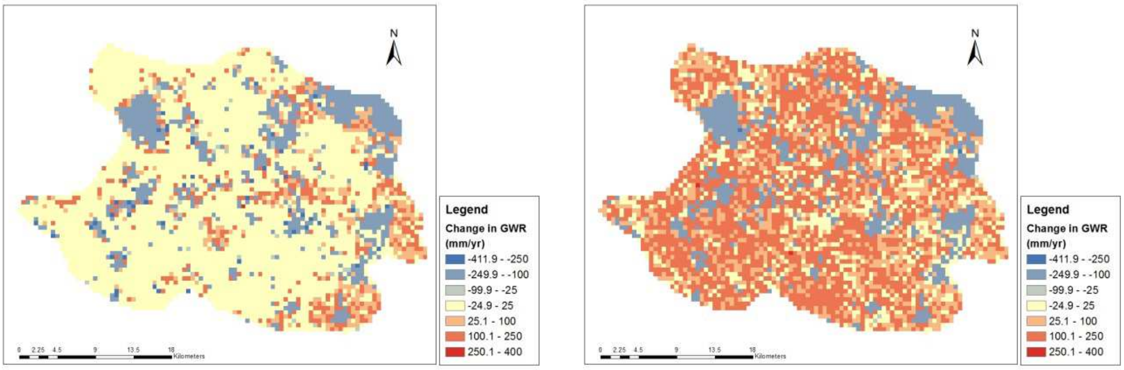


Figure 4.7 Changes in net groundwater recharge to the groundwater table for scenario B2 (left) and B3 (right). Red colors indicate a reduction in recharge while blue colors indicate an increase.

It is clear that recharge is decreased in areas with afforestation and this reduction has an impact on groundwater levels, see Figure 4.8. In scenario B2 a maximum head decrease of approximately 1.5 m is estimated for the top aquifer. At the deeper aquifer (shown to the right) the response is more smoothened but a clear signal is found at the eastern part of the catchment. If the entire catchment is covered by beech (right panel of Figure 4.7 and bottom row of Figure 4.8), groundwater recharge is decreased by up to 250 mm/yr in areas where agriculture has been replaced by beech and the groundwater table is reduced in most of the model area, except at those locations where beech has replaced spruce and in the stream valleys. In the primary aquifer a more averaged picture is found with moderate reductions in hydraulic head.

Based on the flow duration curves from the upstream st. 250020 (Figure 4.5), the B2 scenario only has a small impact on the discharge while a larger reduction is found for scenario B3, where the discharge at exceedance probabilities of 0.1, 0.5 and 0.9 are reduced by 8%, 8% and 5%, respectively. At st. 250082 (outlet) the corresponding numbers are 12%, 14% and 14% for scenario B3. The median minimum value for scenario B2 only show a small change indicating that the increase in yield from replacing spruce by beech counterbalance the decrease from replacing agriculture by beech. For scenario B3 the reduction in median minimum is 4% at station 250020 and almost 9% at station 250082. Hence, the relative impact of scenario B3 on stream discharge is larger for the whole catchment than the upstream catchment.

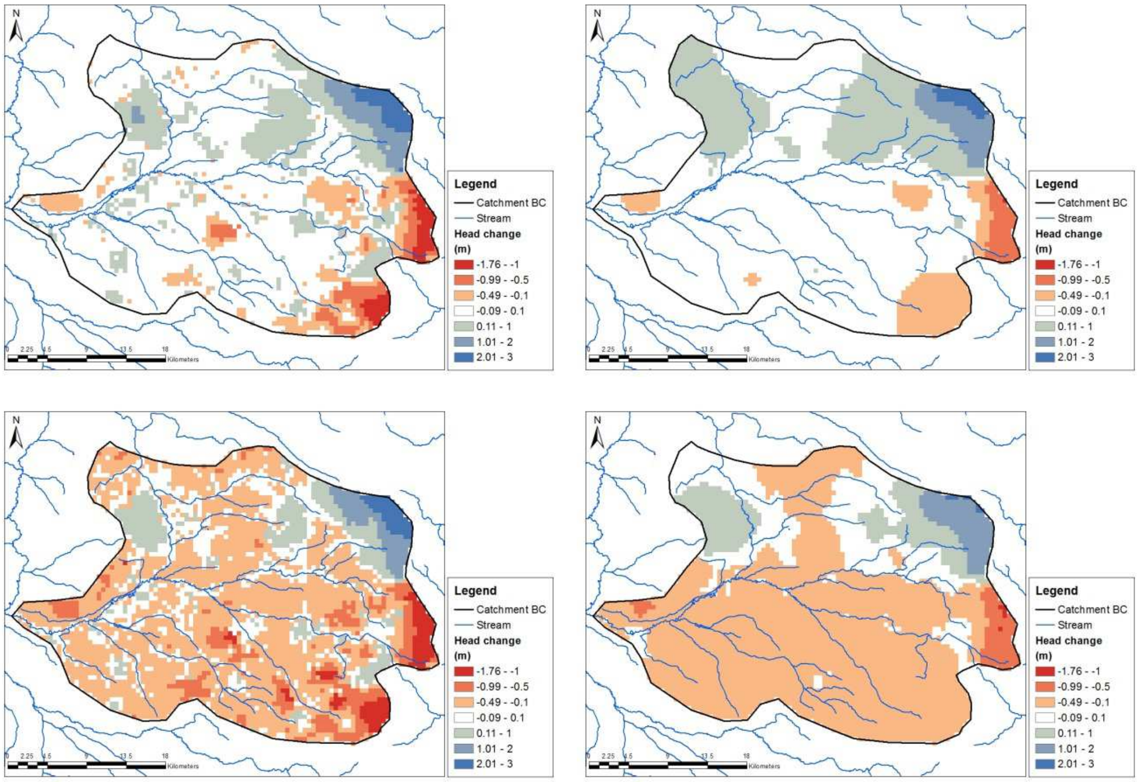


Figure 4.8 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario B2 (top) and B3 (bottom). Right panel: Results for primary groundwater layer for scenario B2 (top) and B3 (bottom).

4.3 Skjern - Afforestation by spruce

In Figure 4.9 the changes in groundwater level for scenario S2 and S3 are presented. In both cases the forest area have been increased by expanding the area with spruce such that the area covered by forest has been doubled (S2) or covers the entire area (S3), see Figure 2.7. When agriculture is replaced by spruce the evapotranspiration increases and the groundwater recharge decrease, see Figures 4.1 and 4.2. The effect on groundwater is clearly seen on Figure 4.9, where the groundwater table decreases by several meters in the eastern area, where spruce has been introduced in scenario S2. In the primary aquifer (top, right panel) the impact of the land used change is recognized in most of the area, with reductions in head values of more than one meter in the easternmost part of the catchment. In Figure 4.5 the effect on stream discharge is shown. Significant impacts are found at st. 250020 with reductions in stream discharge of 13%-16% for exceedance probabilities of 0.1-0.9. Median minimum discharge decreases by almost 13%. At the discharge station at the catchment outlet (250082) reductions of 6%-8% are found for exceedance probabilities of 0.1-0.9, and the median minimum decreases by 8%.

For the S3 scenario the impact on groundwater level is more significant than for scenario S2. The hydraulic head is reduced by several meters in large parts of the catchment, both in the shallow and the deep aquifers (Figure 4.9, bottom panels). The effect on stream discharge is also significant, Figure 4.5. At the upstream station (250020) the flow duration curve is much lower compared to the reference scenario (P1). At exceedance probabilities of 0.1, 0.5 and 0.9 reductions in discharge of 46%, 36% and 32%, respectively, are found and the median minimum values is reduced by 21%. Hence, an increase of the area covered by spruce may have significant impacts on both groundwater and stream discharge. The effect on high flows is especially large with reductions in discharge in the order of 40%-50% at exceedance probabilities of 0.1. The effect on the low flow is somewhat less, with reductions in median minimum values in the order of 20%-30%.

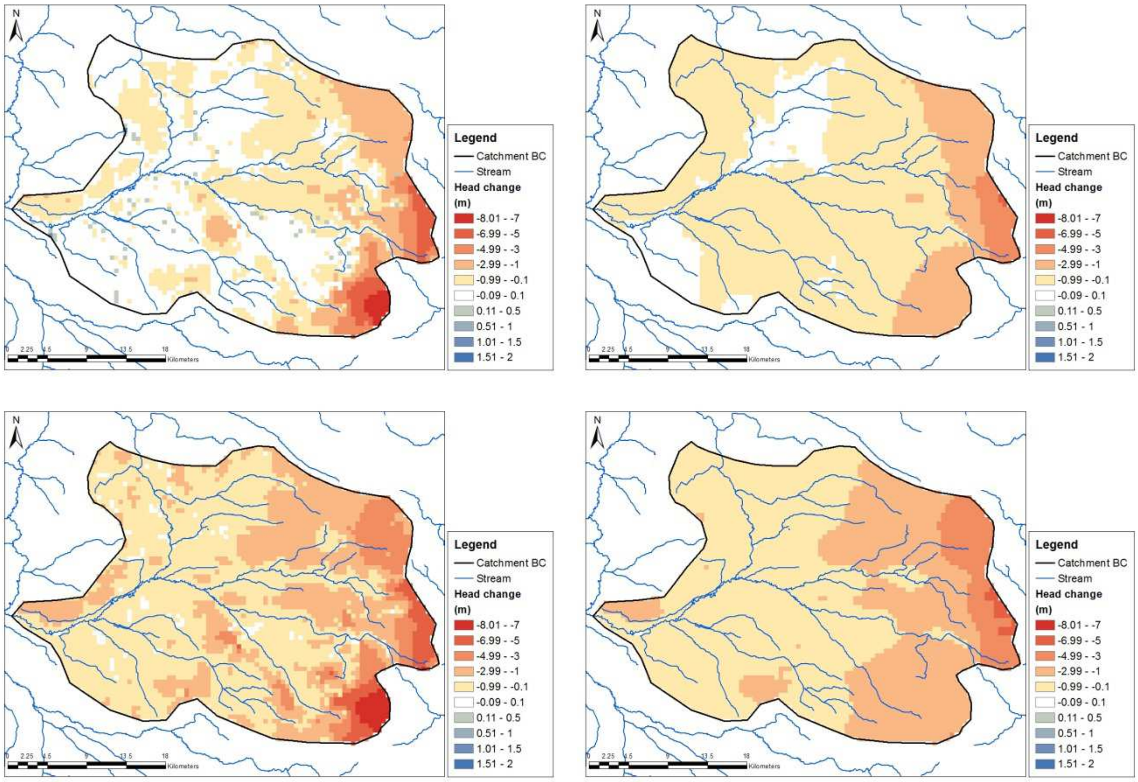


Figure 4.9 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario S2 (top) and S3 (bottom). Right panel: Results for primary groundwater aquifer for scenario S2 (top) and S3 (bottom).

4.4 Skjern - Agricultural scenarios

Results from two additional scenarios are presented. In scenario W1 the forest area is doubled by allocating willow to areas with shallow groundwater and upward flowing groundwater (primarily in the stream valleys, see Figure 2.8). In scenario A1 all forest is removed and replaced by crops with the same statistical distribution as found for the present agricultural areas. The impact of introducing the willow plantations on groundwater is shown in Figure 4.10 (top row). Small reductions in groundwater level are found, both at the shallow and the deep aquifers. The willow has primarily been located in discharge areas. Hence, even though the willow has a higher evapotranspiration than the crops that it replaces, the impact on groundwater level is insignificant. The effect on stream discharge is somewhat more clear, see Figure 4.5. At exceedance probabilities of 0.1, 0.5 and 0.9 the discharge is reduced by 5%, 3% and 2%, respectively, at station 250020, and by 4%, 3% and 3.5% at station 250082. The median minimum values at the two stations are reduced by 1.5% and 2%, respectively. Hence, with the parameterization used here, the effect of planting willow in the discharge areas primarily located in the stream valleys is relatively low. Since willow is not located in areas where groundwater is generated, no impacts on the groundwater resources are observed. And even though the evapotranspiration of the willow is relatively high, because of a small stomata resistance, RSC_{min} (see Table 3), the difference in actual evapotranspiration between willow and the crops that it replaces is not high enough to play a significant effect on stream discharge.

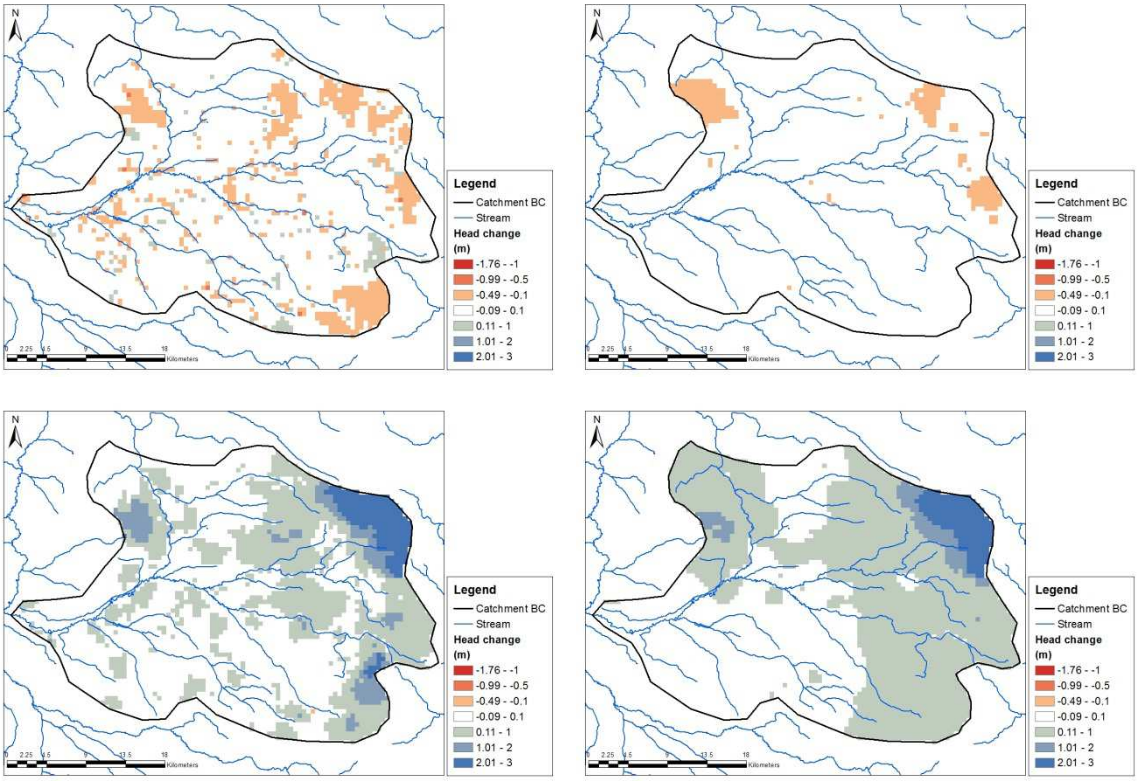


Figure 4.10 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario W1 (top) and A1 (bottom). Right panel: Results for primary groundwater aquifer for scenario W1 (top) and A1 (bottom).

In scenario A1 the impact of removing the entire forest is examined. In Figure 4.10 (lower row) the effect on shallow and deep groundwater is shown. In both aquifers significant increases in heads are found and the effect is larger than for scenario B1, where spruce is replaced by beech. The impact of replacing spruce by agricultural crops is also clearly seen on stream discharge, Figure 4.5. The A1 scenario yields the highest discharge of all the cases analyzed. At st. 250020, an increase in stream discharge of 16%, 13% and 8% are found for exceedance probabilities of 0.1, 0.5, and 0.9, respectively. The corresponding numbers at st. 250082 are 6%, 6% and 5%. Median minimum values increase by 7% and 4% at the two stations. Hence, replacing spruce by agriculture is the most efficient method to increase water yield, both with respect to groundwater and surface water.

4.5 Skjern – Water balance

In Table 5 actual evapotranspiration, groundwater recharge and the components of river flow (overland flow, drain flow and base flow) are listed. When the present forest type (spruce) is replaced by beech (scenario B1) actual evapotranspiration decreases by 23 mm/yr (average for entire catchment) and the groundwater recharge increases by the same amount. For scenario S1-S3 actual evapotranspiration increase with the coverage of forest and the largest effect is found in scenario S3 where an increase of almost 190 mm/yr corresponding to 36% is predicted. As evapotranspiration increase, groundwater recharge decrease resulting in a reduction in stream discharge. The changes in recharge affect overland flow, drain flow and base flow differently, where the relative impact on overland flow and drain flow are highest (reduction of almost 50% in scenario S3) and the impact on base flow is lowest. Hence, the changes in land used have a relatively high impact on the fast flow components like overland flow and drain flow.

Table 5 Changes in 10-year annual mean water balance (mm/yr) for the Skjern Catchment. The absolute values are listed for scenario P1 while changes relative to P1 are listed for the remaining scenarios. Absolute changes are listed first and relative changes are listed in parenthesis. EA denotes actual evapotranspiration. Mean precipitation is 1063 mm/yr. Changes in storage may result in an apparent error in the water balance.

Scenario	EA	Net recharge	Overland flow	Drain flow	Base flow
P1	519	547	30	269	216
B1	-23 (-4%)	+23 (+4%)	+3 (+10%)	+10 (+4%)	+5 (+2%)
B2	-11 (-2%)	+11 (+2%)	+1 (+3%)	+4 (+1%)	+2 (+1%)
B3	+63 (+12%)	-61 (-11%)	-5 (-17%)	-53 (-20%)	-7 (-3%)
S1	0 (0%)	-1 (0%)	0 (0%)	-3 (-1%)	0 (0%)
S2	+36 (+7%)	-37 (-7%)	-5 (-17%)	-20 (-7%)	-12 (-6%)
S3	+189 (+36%)	-185 (-34%)	-14 (-47%)	-129 (-48%)	-39 (-18%)
W1	+17 (+3%)	-17 (-3%)	-1 (-3%)	-15 (-6%)	-4 (-2%)
A1	-37 (-7%)	+36 (+7%)	+5 (+17%)	+18 (+7%)	+8 (+4%)

4.6 Lejre river catchment – from spruce to beech

In Figure 4.11 the total evapotranspiration from the Lejre catchment for scenario P1 and B1 is illustrated (left panels). At the places where beech has substituted spruce a significant decrease in total evapotranspiration is found (compare the left column figures). The change is explained by the differences in interception loss which is illustrated to the right. The interception loss is larger than 200 mm/yr in the spruce plantations while it is less than 100 mm/yr in the beech forest. Although these changes are significant, the effect is smaller than for the Skjern area, Figure 4.4.

This difference has a pronounced effect on the groundwater recharge at these locations and therefore also on the groundwater table, see Figure 4.12. The groundwater table is found to increase by up to one meter at the locations where the land use has been changed. In the deep aquifer an increase in head values of more the 10 cm is found in the western half of the model area.

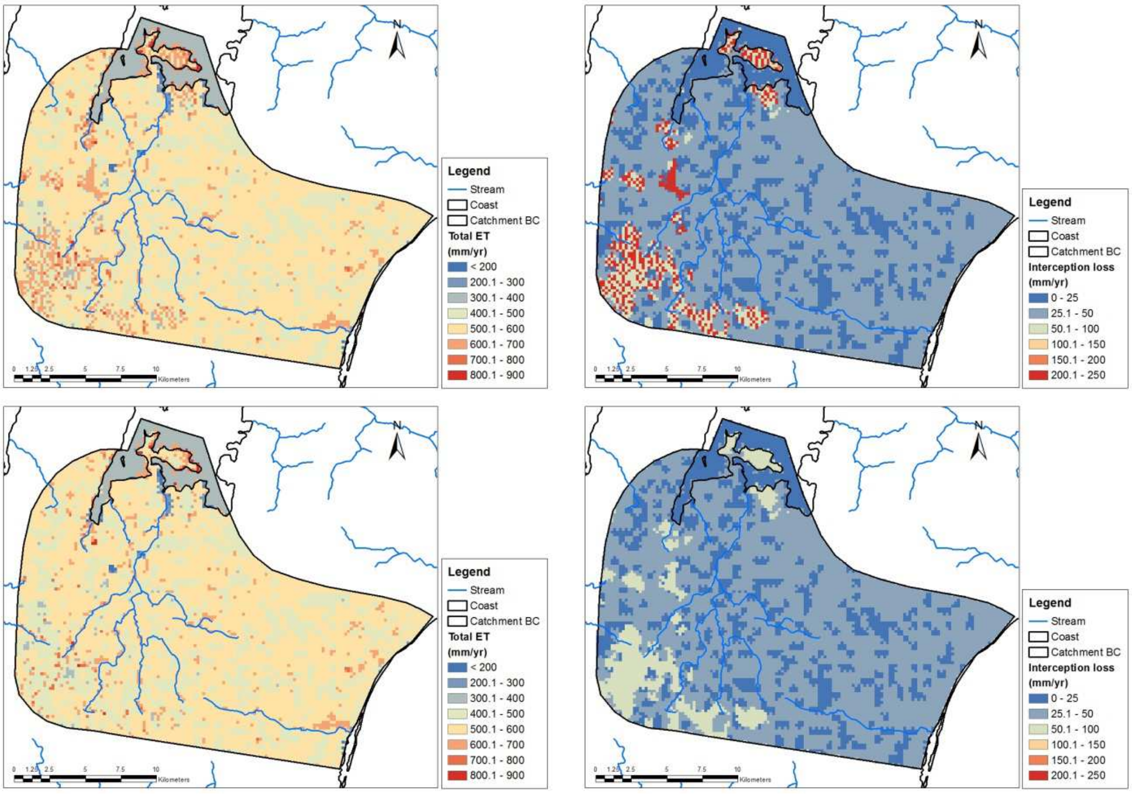


Figure 4.11 Total evapotranspiration (left panel) and interception loss (right panel) for the Lejre catchment with land use scenario P1 (top row) and scenario B1 (bottom row).

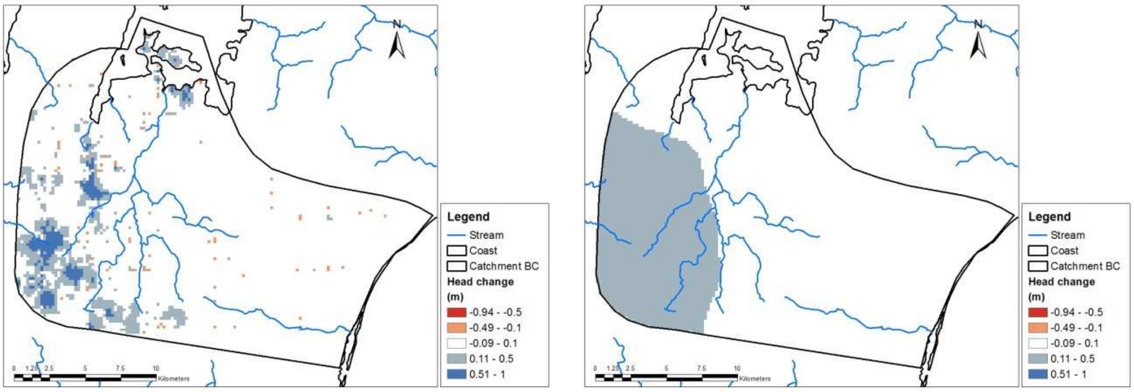
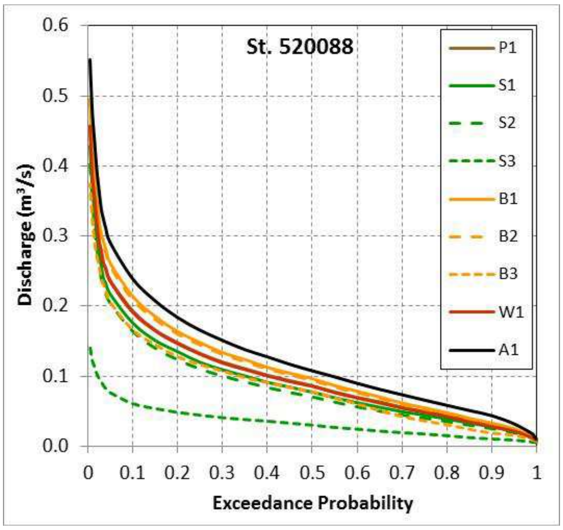


Figure 4.12 Difference in hydraulic head values for scenario B1 compared to scenario P1. Left panel represents the upper aquifer while the right panel represents the deep chalk aquifers.

In Figure 4.13 the flow duration curves for st. 520088 (upstream) and 520068 (downstream) (see Figure 2.2 for locations) are presented. At the upstream station, scenario B1 results in an increase in the flow duration curve with values that are 9%-11% higher at exceedance probabilities of 0.1 to 0.9. At st. 520068 the relative impact is lower. At exceedance probabilities of 0.1 – 0.9 the discharge increase by 2%-3%.



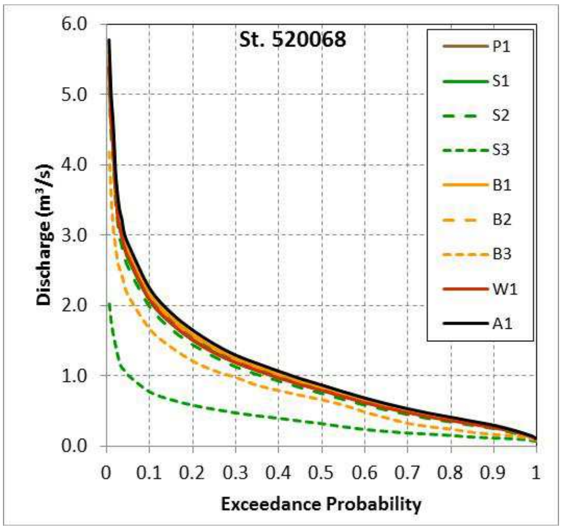


Figure 4.13 Exceedance probability at discharge station no. 520088 (left) and no. 520068 (right) for the defined land use scenarios. Scenario P1 is hidden below the red curve representing scenario W1.

The median minimum value, Figure 4.14, for scenario B1 is 7% higher at the upstream station 520088 and 2% higher at the downstream station 520068, than in scenario P1.

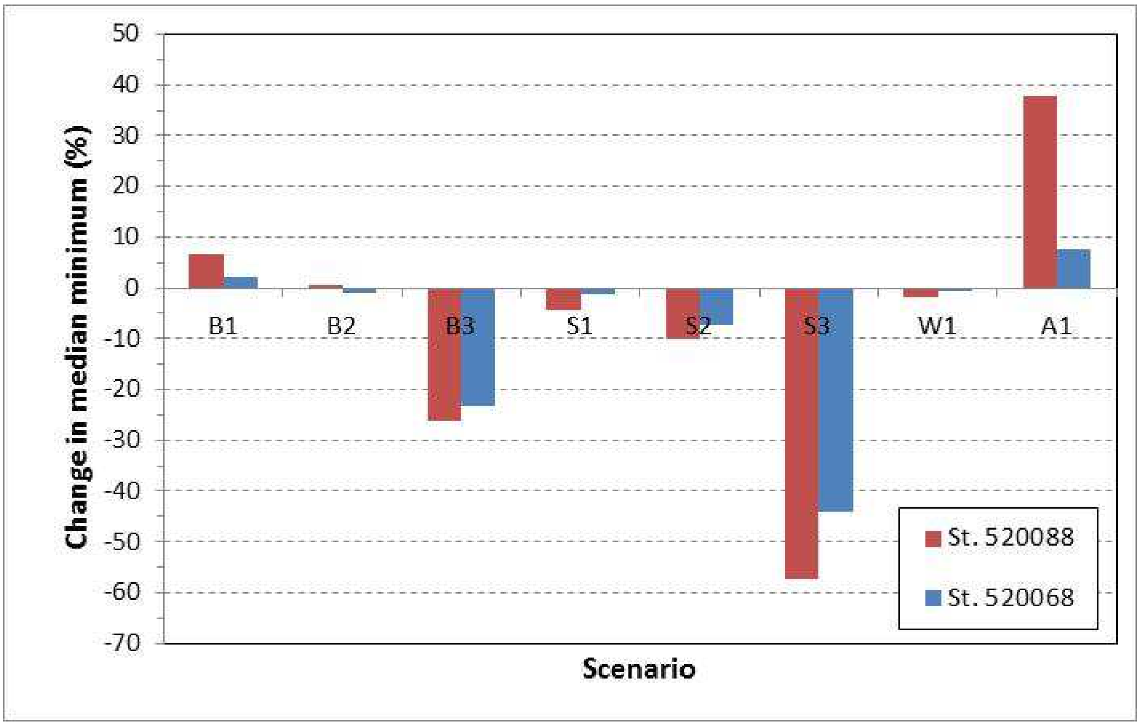


Figure 4.14 Change in median minimum at station no. 520088 (upstream) and no. 520068 (downstream) compared to the reference scenario (P1).

4.7 Lejre - Increasing area with forest

When the area with forest is increased by a factor of two (scenario B2) the groundwater level is reduced in the areas where beech have replaced agriculture, see Figure 4.15 (upper left). The groundwater level drops by up to 1 m. At the deep aquifer the impact of the land use change is smaller and limited to the north-eastern area. The impact of increasing groundwater recharge in places where beech has replaced spruce is almost counterbalanced by the effect from decreasing recharge in areas where beech has replaced agriculture. This is also clearly seen on the flow duration curve and the median minimum value. Upstream (st. 520088) the increase in discharge at exceedance probabilities of 0.1, 0.5 and 0.9 is estimated to 8%, 9% and 3%, and the median minimum values increase by less than 1%. Downstream (st. 520068) the impact on the flow duration curve is even smaller with a relative change between -1% and +1%. Similar results were found at the Skjern River catchment and indicate that it is possible to increase the forest area in Denmark by a factor of two without compromising the groundwater resources if the current conifer forest at the same time is substituted by beech.

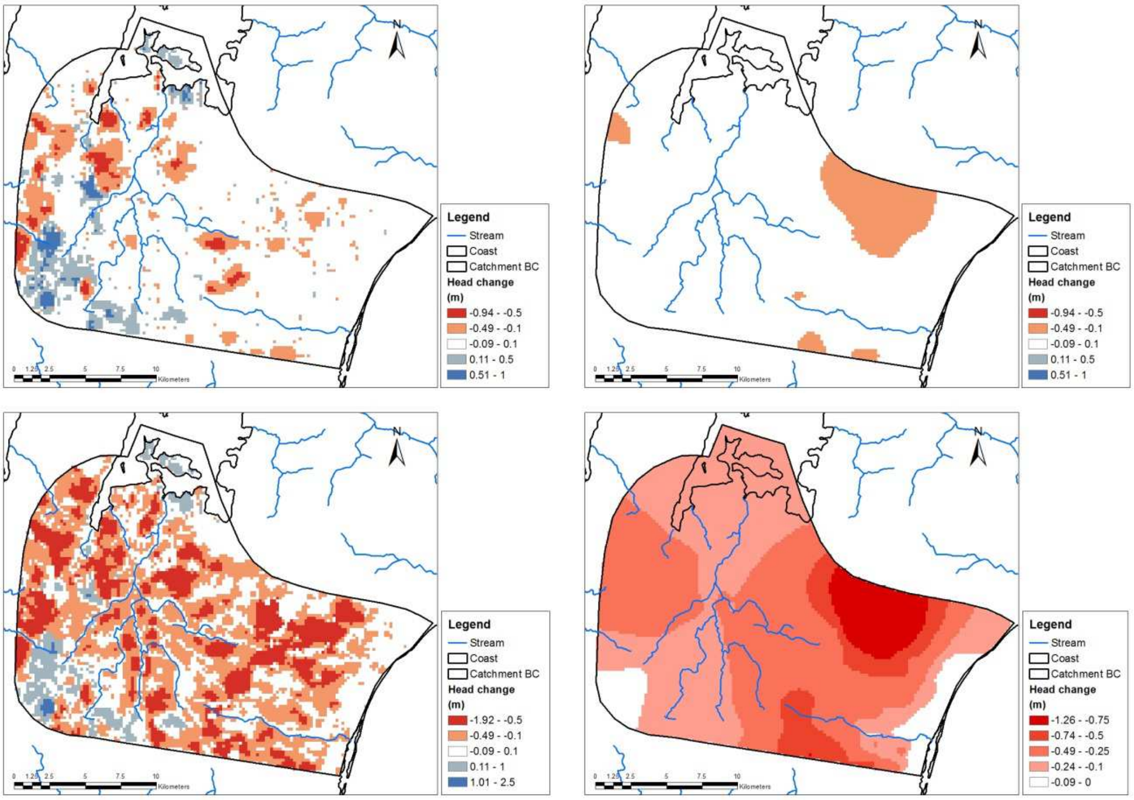


Figure 4.15 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario B2 (top) and B3 (bottom). Right panel: Results for primary groundwater layer for scenario B2 (top) and B3 (bottom).

In Figure 4.16 the change in groundwater recharge for scenario B3 is shown. At places where beech has replaced spruce an increase in recharge is found (blue areas), while large reductions in recharge is found in areas where beech has replaced agriculture (red areas). The resulting effect on the groundwater level is significant, see Figure 4.15 (bottom row). In the top aquifer most of the area experiences a reduction by more than 10 cm, and in a significant part of the area the reduction is larger than 0.5 m. In the deep aquifer the effects is also significant. Nearly all the area is affected and in more than half of the area the hydraulic head is reduced by more than 25 cm. With respect to stream flow, scenario B3 results in significant reductions in flow at both stations (Figure 4.13). Upstream (st. 520088) reductions of 14%, 10% and 38% are found at exceedance probabilities of 0.1, 0.5 and 0.9, and the median minimum value is reduced by 26%. Similar results are found at the downstream st. 520068 where reductions in stream discharge of 22%, 20% and 40% are found at exceedance probabilities of 0.1, 0.5 and 0.9, and the median minimum values is reduced by 23%. Hence, if the entire catchment (excluding cities) were covered by beech both the stream discharge and the groundwater level would be significantly reduced.

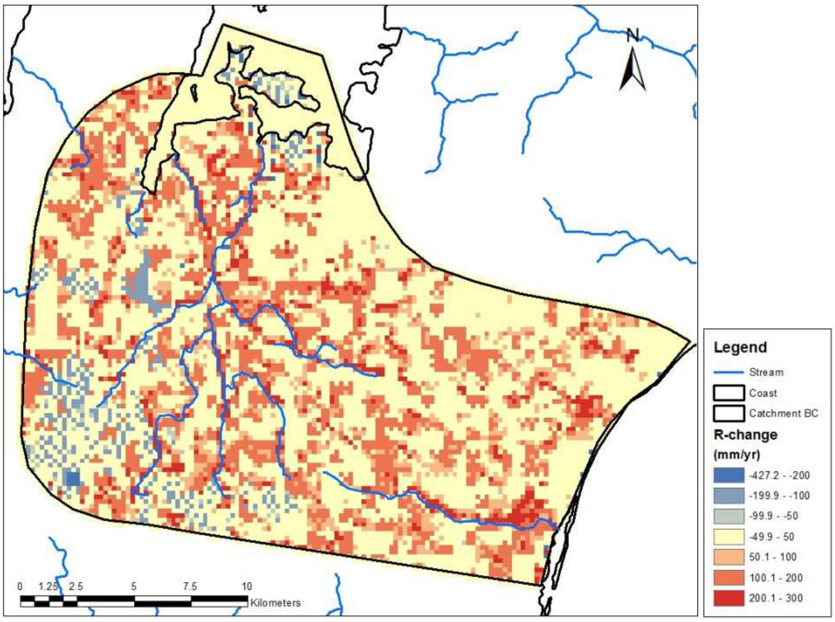


Figure 4.16 Changes in net groundwater recharge to the groundwater table for scenario B3.

4.8 Lejre - Afforestation by spruce

In Figure 4.17 results from scenario S2, where the forest area has been doubled and scenario S3 where the entire forest area is defined by spruce, are presented.

The S2 scenario results in relatively large changes in groundwater level, both in the upper and the deep aquifer, with reductions of more than 3 m in some locations. The impact is also significant with respect to stream discharge, see Figures 4.13 and 4.14. The discharge is reduced by 15%-19% at the upstream station and by 7%-10% at the downstream station.

If the entire area is covered by spruce, scenario S3, even larger reductions in groundwater level and stream discharge are found. The groundwater level is predicted to decrease by several meters in large parts of the catchment, both in the shallow and the deep aquifers. The impact on stream discharge is very strong. At st. 520088 the discharge is expected to decrease by approximately 60% while the effect at the downstream station is found to be between 63% reduction at an exceedance probability of 0.1 and 44% reduction in the median minimum value. Hence, the effect is strongest for the high flows. This tendency was also found for the Skjern catchment.

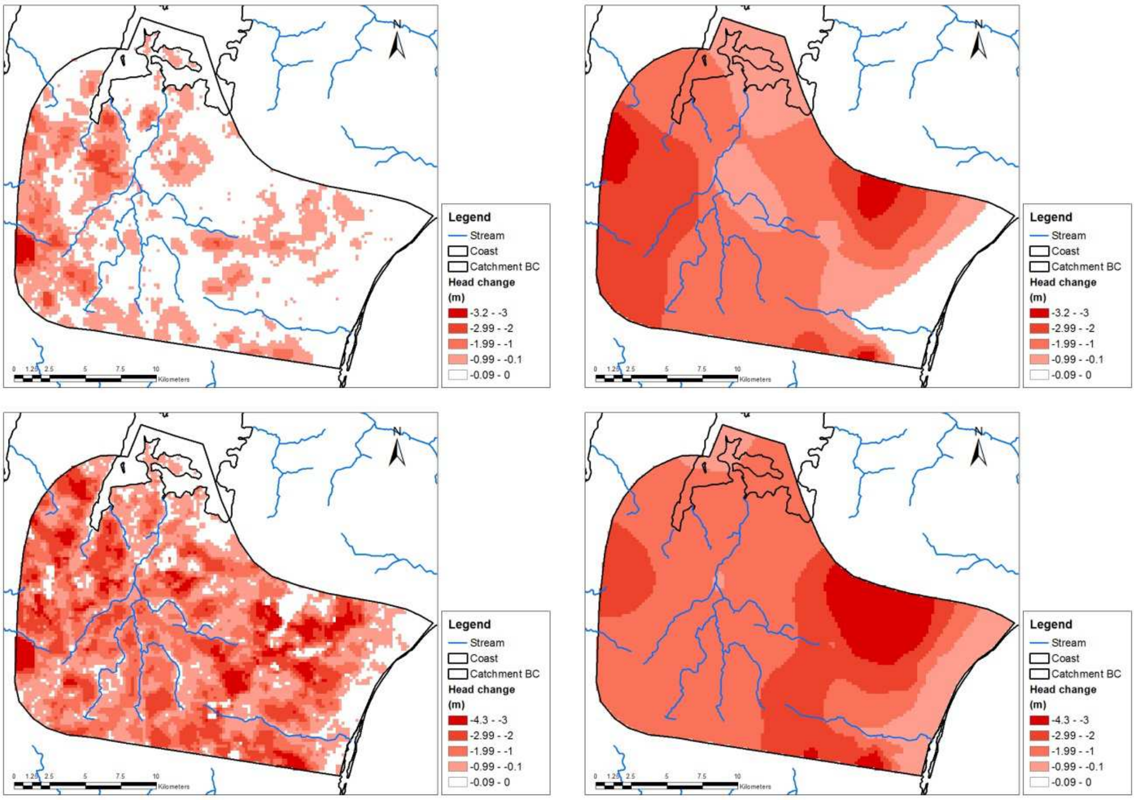


Figure 4.17 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario S2 (top) and S3 (bottom). Right panel: Results for primary groundwater layer for scenario S2 (top) and S3 (bottom).

4.9 Lejre - Agricultural scenarios

In Figure 4.18 results on the change in groundwater level for scenario W1, where the forest area has been doubled by planting willow in areas with shallow groundwater, is presented. The impact on groundwater is very limited, both in the shallow aquifer but especially in the deep aquifer where the changes in head is less than 10 cm. For stream discharge the impact is slightly larger, with reductions in stream discharge as a result of willow plantations of up to 7%.

The effect is much larger if agricultural crops replace the current forest (scenario A1), see Figure 4.18 (bottom row). The effect is also significant in the deep aquifer, where increasing hydraulic heads of up to 0.5 m is found in the south-western part of the model area. Also stream discharge is found to increase. At the upstream station the discharge increase by 24%, 25% and 43% at exceedance probabilities of 0.1, 0.5 and 0.9 while the effect at the downstream station is significantly lower, with corresponding values of 5%, 6% and 7%.

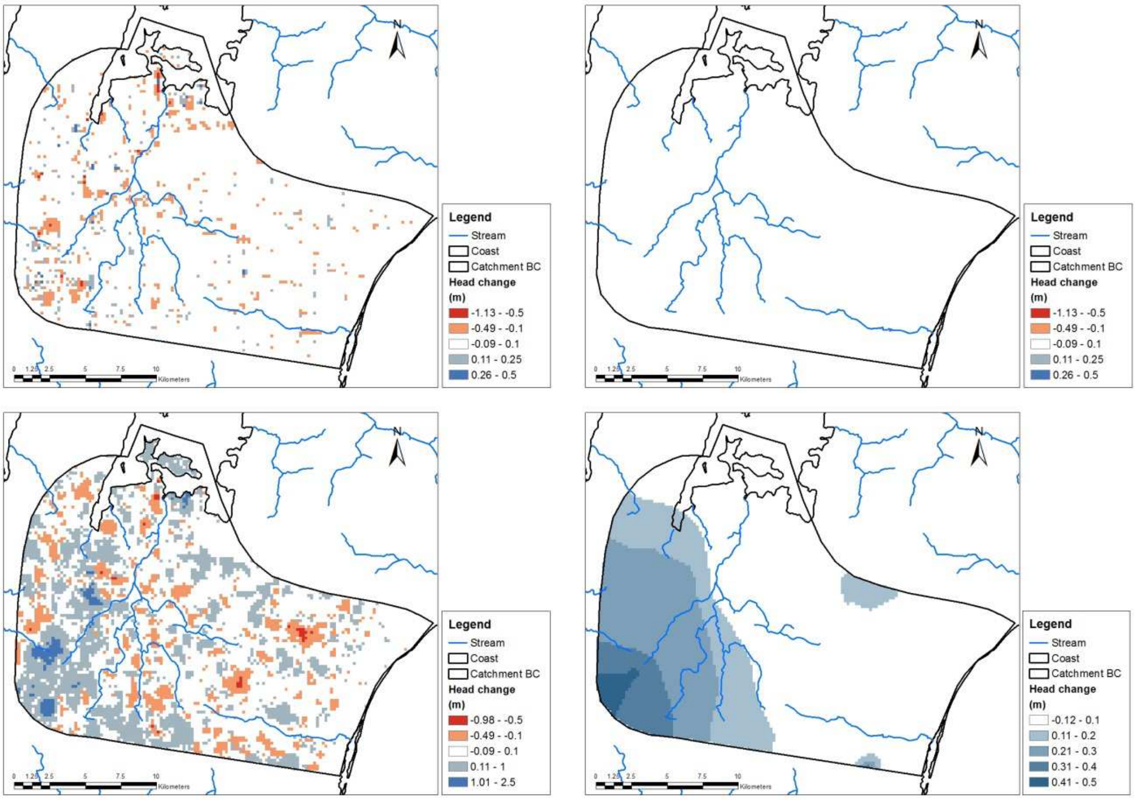


Figure 4.18 Changes in hydraulic head compared to scenario P1. Left panel: Results for upper groundwater layer for scenario W1 (top) and A1 (bottom). Right panel: Results for primary groundwater layer for scenario W1 (top) and A1 (bottom).

4.10 Lejre – Water balance

In Table 6 water balance results for the catchment to discharge station 520068 in the Langvad stream system is listed. First, it should be noticed that the actual evapotranspiration under current conditions has the same magnitude (520 mm/yr) as in the Skjern catchment (Table 5) even though the precipitation in the Skjern catchment is more than 250 mm higher per year. This shows the effect of the clayey soil type where water can be stored much better than in the sandy soils in Skjern. Another clear difference is how the stream flow is distributed between overland flow, drain flow and base flow. In the Lejre area drain flow dominates the discharge while drain flow and base flow are comparable in Skjern.

With respect to the changes induced by the land use, the same tendencies as found for Skjern are observed; however, the magnitudes are higher. If Tables 5 and 6 are compared, it is clear that the impacts on overland flow and drain flow are more significant at the Landvad Stream catchment than at the Skjern catchment, even though the fraction of the total area affected by land use changes in all scenarios is larger in Skjern.

A similar result is found by comparing the median minimum values from Skjern and Lejre, Figures 4.6 and 4.14. The changes found for the Langvad catchment are in most cases higher than those found for the Skjern catchment, even though the area with forest in the present situation (scenario P1) is higher for Skjern than for Langvad.

Table 9 Changes in 10-year annual mean water balance (mm/yr) for the catchment to station 520068 in the Lejre area. The absolute values are listed for scenario P1 while changes relative to P1 are listed for the remaining scenarios. Absolute changes are listed first and relative changes are listed in parenthesis. EA denotes actual evapotranspiration. Mean precipitation is 801 mm/yr. Changes in storage may result in an apparent error in the water balance.

Scenario	EA		Net recharge		Overland flow		Drain flow		Base flow	
P1	520		278		3		182		5	
B1	-5	(-1%)	+5	(+2%)	0	(+4%)	+5	(+3%)	0	(0%)
B2	-1	(0%)	+1	(0%)	0	(0%)	1	(+1%)	0	(0%)
B3	+49	(+9%)	-48	(-17%)	-1	(-46%)	-45	(-25%)	0	(-6%)
S1	+6	(+1%)	-6	(-2%)	0	(-4%)	-5	(-3%)	0	(-2%)
S2	+17	(+3%)	-17	(-6%)	-1	(-19%)	-15	(-8%)	0	(-6%)
S3	+137	(+26%)	-136	(-49%)	-2	(-85%)	-119	(-65%)	-2	(-33%)
W1	+6	(+1%)	-6	(-2%)	0	(-12%)	-6	(-3%)	0	(-2%)
A1	-12	(-2%)	+12	(+4%)	0	(+8%)	+11	(+6%)	0	(+2%)

5. Discussion

The results from this study demonstrate that water yield strongly depends on land use and is controlled by species characteristics such as vegetation height, leaf area index and growing period. Interception loss is found to be significantly higher from conifers like spruce compared to other vegetation types including beech and agricultural crops. Annual interception loss from spruce plantations is relatively high, primarily because the spruce carry leaves during the winter season whereas beech and cereal crops do not with the oceanic climate in Denmark. The higher interception loss from spruce results in higher total ET and lower groundwater recharge. Hence, substituting spruce by beech results in increasing groundwater recharge and stream discharge. In the Skjern catchment, where nearly all forest is defined as spruce and the effect therefore is relatively high, an increase of approximately 150 mm/yr is found at the places where forest is located and on average for the entire catchment a value of 23 mm/yr is found.

The results from both Skjern and Lejre indicate that afforestation results in decreasing stream discharge and the effect is especially strong for spruce. In the case where the entire catchment is covered by spruce (scenario S3), the flow duration curves drop significantly for both Skjern and Lejre. Compared to the scenario where agricultural crops cover the entire catchment (A1) a reduction in the median minimum value of approximately 25% for Skjern and 50% for Lejre are found. However, the impact on high flows is much larger. At an exceedance probability of 0.1 a reduction in discharge in the Skjern catchment of 40% is found, while the corresponding value for the Langvad stream catchment is 65%. The relative impact is even larger at lower exceedance probabilities. This indicates that afforestation has the potential to mitigate extreme flow, with an impact on low flows that is less severe.

Land used changes have a stronger impact on groundwater at Skjern than at Lejre, while stream discharge is affected more in Lejre than in Skjern. This is primarily caused by the differences in the properties of the shallow soils. While the top soils of the Skjern catchment are sandy and precipitation percolates easily, much of the infiltrating water in Lejre is captured by the drainage system (tile drains, ditches, small streams). Therefore, a higher fraction of additional groundwater recharge is routed through surficial flow paths (overland flow, drain flow).

The method used to quantify the impact of land use change is relatively advanced. The groundwater zone is described by a 3D geological and numerical model that describes deep aquifers, confining layers and unconfined aquifers. The groundwater zone interacts with an unsaturated zone where the water flow is described by Richard’s equation. The soil in the root zone is described by a three layer model that accounts for the differences in hydraulic properties in the A, B and C horizon. The unsaturated zone is connected to an energy based description of evapotranspiration that includes interception loss from the canopy, transpiration from the leaves and evaporation from the soil surface. The actual evapotranspiration is controlled by atmospheric climate data and physically based parameterization of the vegetation and the soil. Hence, the method used to assess the impact of land use changes on catchment scale is considered to be the most comprehensive that has been presented in Denmark.

However, the results are associated with a number of uncertainties. The basis for the current scenario runs is a parameterization of spruce, beech and agriculture that results in different levels of evapotranspiration from the different vegetation types. The uncertainty on the vegetation parameters is relatively high. However, the differences in evapotranspiration between vegetation typess are partly controlled by the timing and length of the growing season and hence when the vegetation carries leaves. Relatively small uncertainty is associated to this part.

In the current study the effect of land use change on evapotranspiration has been isolated. However, land use changes are expected to result in other effects, including modifications of the drainage system, the infiltration capacity of the soil surface and the roughness of the soil surface to overland flow. As an example, afforestation is expected to result in degradation of the drainage system that exists when the land is managed by farmers. Tile drains are normally not installed in forest as their roots will damage the drains. Instead, ditches are normally installed, however, with larger spacing and at shallower depth than the tile drains.

The impact of land use will also be affected by rainfall dynamics. Precipitation dynamics will affect interception loss as many small rainfall events will result in higher interception loss than a few large rainfall events. Hence, it is important to provide data with an accurate description of the temporal heterogeneity of rainfall. It would be relevant to analyze the impact of rainfall dynamics on interception loss and hence on the impact of land use type on water balances.

6. Conclusions

Using a physically based and spatially distributed hydrological model with an energy based description of evaporation and transpiration processes, two large scale models have been established; one for an area in Western Denmark dominated by sandy soils and one for an area in Eastern Denmark dominated by loamy soils. Several land used scenarios have been defined to test the impact of forest type and coverage on water resources. The main conclusions from the project are:

(1) When conifer forests are replaced by broadleaf forests a significant increase in groundwater recharge and groundwater level is expected. This is explained primarily by a reduction in interception loss during winter season where the beech forest is without leaves and therefore has no evaporation from interception storage.

(2) The area covered by forest can be doubled without compromising the groundwater resources or the minimum stream discharge if afforestation is carried out with broadleaves and the present conifer forest simultaneously is substituted by broadleaf forest.

(3) If the land use of the entire catchment is changed from agriculture to forest, significant reductions in groundwater level and stream discharge may be expected, especially if the forest consists of conifer trees.

(4) The results indicate that the impact of increasing the forest area on stream discharge is stronger for the Lejre area than for the Skjern area. In Lejre the shallow geology is dominated by clayey moraine deposits which limit the conductivity of the sub-surface. Hence, if groundwater recharge is increased the extra water is prone to discharge through near surface routes such as overland flow or drain flow. In contrast, the sandy soils in Skjern enable the additional groundwater recharge to flow through the groundwater aquifers. The effect of land use change on the groundwater resources will therefore be larger at the Skjern river catchment than at the Lejre catchment.

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Mere vand fra skove

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