FACULTEIT WETENSCHAPPEN

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Farming systems in Lake Tana basin, Ethiopia: Land surface management and its impact on runoff response

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“ከዘራ ገበሬ ያቦየው ይበልጣል”

[“A farmer who made traditional ditches is by far better than one who sowed”]

Farmer from North Shewa, Ethiopia, cited by Million (1996, p. 168)

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NEDERLANDSTALIGE SAMENVATTING

1. INLEIDING

1.1 Het gebruik van drainagekanalen en hun impact

De oppervlakkige waterafstroom (runoff) ten gevolge van seizoenale saturatie van de bodem veroorzaakt erosie. Wanneer runoff zich concentreert, kan dit leiden tot rillerosie of ravijnvorming. Het hoofdzakelijke doel van het gebruik van drainagekanalen op hellend akkerland is om de tijdelijke overmaat aan water af te voeren om de negatieve effecten ervan op de gewassen te verkleinen. Het gebruik van drainagekanalen schept een hele waaier aan positieve effecten wat de wereldwijde toepassing ervan verklaard, zoals bijvoorbeeld: het vermijden van bodemcompactie door vee op een gesatureerde bodem, een verhoogd zuurstofgehalte in de bodem, beter kiemen van het gewas, en een diepere wortelzone. Daarnaast moeten ook on-site en off-site negatieve effecten van het gebruik van drainagekanalen in beschouwing worden genomen. Voorbeelden van besproken off-site effecten van drainagekanalen zijn een verhoogde sedimentlading, een hoger piekdebiet of de vorming van ravijnen. On-site effecten zijn in mindere mate besproken, al zijn voorbeelden van on-site ravijnvorming gekend. Er is nog geen consensus over de finale balans van de positieve en negatieve effecten van het gebruik van drainagekanalen. Naast de effecten van drainagekanalen op de erosieprocessen in het landschap kan het gebruik ervan ook leiden tot conflicten tussen naburige landbouwers.

In het Tana bekken speelt de seizoenale neerslag een belangrijke rol voor de gewasteelt, waar het groeiseizoen beperkt is tot de duur van het regenseizoen met een aaneensluitende periode van residueel vocht. Men spreekt ook wel van regenafhankelijke landbouw. Tijdens het regenseizoen worden traditionele drainagekanalen op gecultiveerde hellingen geconstrueerd in sub-humide regio’s van Ethiopië. Deze drainagekanalen worden in het Tana bekken ook wel *feses* genoemd. Landbouwers zijn op de hoogte van de eventuele negatieve impact van het gebruik van drainagekanalen op hun akkerland. Zo alterneren ze bijvoorbeeld de positie van de *feses* ieder jaar omdat deze anders dieper zouden worden. Toch worden ze gebruikt als een bodem- en waterconserveringstechniek (BWC) dat efficiënt blijkt te zijn om erosie door runoff dat op een ongecontroleerde manier over het land stroomt te beperken als stone bunds (steenhopen parallel aan de hoogtelijnen) niet aanwezig zijn.

1.2 Probleemstelling

Door een stijgende bevolkingsdruk in Ethiopië neemt ook de druk op het land toe en worden zelfs steile gebieden omgevormd tot akkerland. Het bodemverlies door watererosie vormt een bedreiging voor de traditionele landbouw en de nationale economie in Ethiopië. Het verlies aan regenwater vormt een ander probleem. Het maken van drainagekanalen heeft positieve effecten op het akkerland, al ziet men vaak het gebruik ervan aan als wanbeheer van het akkerland met on-site en off-site degradatie tot gevolg. De impact van drainagekanalen op het milieu kan niet eenduidig gesteld worden omdat het een complex geheel van effecten omvat. Rillerosie en ravijnerosie vormen de belangrijkste processen van landdegradatie door water. Daarom is het gebrek aan kennis over (1) het proces van ravijnvorming en (2) de effecten van het gebruik van artificiële drainagekanalen op het milieu problematisch. Om deze redenen stellen we dat een uitgebreide analyse van de hydrogeomorfologische effecten van artificiële drainagekanalen vereist is. De specifieke onderzoeksdoelstellingen voor deze dissertatie zijn:

- Verklarende factoren zoeken voor de constructie en het gebruik van drainagekanalen.
- Analyseren van de on-site en off-site hydrogeomorfologische impact van het gebruik van drainagekanalen.
- Beoordelen van de kwetsbaarheid van akkerland voor bodemerosie in relatie tot een specifiek land management.

2. METHODEN EN MATERIALEN

2.1 Studiegebied

De studie situeert zich in het Tana bekken. Meer dan de helft van het Tana bekken wordt gebruikt voor landbouw. Het meest gebruikte productiesysteem is het graan-ploeg complex dat onder druk staat door de bevolkingsgroei en de dalende bodemvruchtbaarheid. Traditioneel wordt er in het Ethiopische hoogland met de *maresha* ploeg geploegd. Deze ploeg wordt getrokken door twee ossen. De Ethiopische hooglanden worden beschreven als een fragiel milieu onderhevig aan landdegradatie, waardoor de duurzaamheid van de traditionele landbouw in het geding komt. Aan de basis van deze degradatie liggen niet enkel de natuurlijke fenomenen (bv. intense neerslag, droogte, …), maar ook de politiek gestuurde wijze van productie en de gerelateerde bodemconservering strategieën. BWC zijn momenteel de meest verspreide vorm van landbouwintensificatie in het Ethiopisch hoogland. In het Tana bekken zijn positieve resultaten geboekt door middel van het gebruik van stone bunds.

Het Tana meer is het grootste meer in Ethiopië met ongeveer 3 miljoen inwoners in het bekken. Het bekken is 16,500 km² groot met de oppervlakte van het meer inbegrepen. Het meer situeert zich in het noordwesten van Ethiopië en vormt een depressie in het Ethiopisch hoogland op 1786 m. Er heerst een "koel tot koud tropisch hoogland moesson" klimaat in het Tana bekken. De gemiddelde temperatuur is 18 °C ± 4 °C. Er heerst een seizoensgebonden neerslagpatroon met meer dan 70% van de neerslag dat valt tijdens het *Kiremt* seizoen (juni-september) met een jaarlijks gemiddelde van 1,421 mm. Het Tana bekken vormt een belangrijk gebied voor Ethiopië door de aanwezigheid van een grote zoetwaterbron, een bron van vissen, biodiversiteit, hydro-elektrische energie, toerisme, etc. De bodems in het bekken zijn zeer vruchtbaar door de aanwezigheid van lacustrine afzettingen en verweerde basalt.

Veldwerk vond plaats tijdens het regenseizoen van 2013 in twee bekkens in de buurt van Wanzaye: Kizin en Wonzima. Een huisje werd voor twee maanden gehuurd in Wanzaye van waaruit te voet naar de studiegebieden werd vertrokken, vergezeld door een lokale vertaler. Daarnaast werden nog twaalf data collectors aangenomen en verloond door het WASE-TANA project om neerslag- en runoff metingen te doen. De Kizin en Wonzima bekkens maken deel uit van het Gumara bekken. Beide bekkens zijn matig tot dominant gecultiveerd. Er zijn drie land management technieken in het gebied te onderscheiden: (1) het exclusieve gebruik van *feses*, (2) het exclusieve gebruik van stone bunds, en (3) een combinatie van zowel *feses* als stone bunds. Er werden tien sub-bekkens geselecteerd in de Kizin en Wonzima bekkens waarvoor de densiteit van *feses* en stone bunds varieerde.

2.2 Biofysische karakteristieken van de tien sub-bekkens

Tien studiegebieden werden eerst afgebakend met een draagbare GPS. De afbakening van de bekkens gebeurde startend vanaf de outlet waarna vervolgens stroomopwaarts het gebied werd geëvalueerd naar waar het water zou stromen tijdens een runoff evenement. Hierna werden kenmerken van de bekkens gedetailleerd opgemeten en gemonitord. Het drainagesysteem werd in kaart gebracht door de GPS punten die genomen werden langsheen de *feses* met een GIS software (ArcMap 10.1) te analyseren. De locaties van stone bunds waren gebaseerd op Google Earth beelden in combinatie met terreinfoto's die ook werd ingevoerd in dezelfde GIS omgeving. Monitor stokken werden geplaatst langsheen enkele *feses* per studiegebied om de evolutie ervan op te meten. De exacte locatie van deze monitor stokken kon niet behouden worden door de intense neerslag, spelende kinderen…, echter werden de monitor stokken op ongeveer dezelfde plaats teruggezet om een kwalitatieve analyse uit te voeren aan de hand van foto's genomen doorheen de tijd op deze monitor sites. De oppervlakte stenigheid werd bepaald door op meerdere plaatsen per studiegebied een systematische observatie uit te voeren (n= 100) langs een rechte lijn. Er werden drie staalnamecampagnes uitgevoerd doorheen de tijd (19 juli, 12 augustus en 5 september) met behulp van Kopeckey ringen om de evolutie het bodemvochtgehalte en de bulkdensiteit te analyseren. Hiervoor werden de stalen 24 uur gedroogd in de oven van het bodemlaboratorium in de universiteit van Bahir Dar. Daarnaast werden er ook één keer gestoorde stalen genomen in de studiegebieden om de silt/klei ratio te berekenen aan de hand van analyses met de sedigraaf in het laboratorium van de universiteit van Gent. De bodemdiepte werd opgemeten op minimum vier plaatsen (of twee voor kleinere studiegebieden zoals de bekkens 7 en 10). Hiervoor werd een metalen staaf gebruikt om de grond los te maken en met de hand te verwijderen om de schade aan het akkerland te beperken. Landbouwers in en rond de studiegebieden werden geïnterviewd om hun motivatie voor het gebruik van een bepaalde land management techniek te bevragen.

Twee regenmeters werden gemaakt naar analogie met de NMSA regenmeters. Deze werden geplaatst in Tashmender (Kizin bekken) en Gedam (Wonzima bekken). De regenmeters werden 's ochtends en 's avonds afgelezen door studenten of landbouwers die in de buurt woonden en konden lezen of schrijven. Eén datacollector voor elk studiegebied werd opgeleid om tijdens runoff evenementen de hoogte van de waterstand in de outlet van het bekken op te meten met een interval van vijf minuten. Met behulp van rating curves werden deze routinemetingen omgevormd naar continue debieten. Rating curves worden gemaakt door het opmeten van de snelheid bij een bepaalde waterhoogte in de outlet door middel van een drijvend object. Door een tekort aan tijd en de onvoorspelbaarheid van de neerslagevenementen was het niet mogelijk om voor elk sub-bekken deze methode toe te passen. Als alternatief werd er dan gebruik gemaakt van de formule van Manning, waarvoor het gemiddelde van de geschatte waardes voor de parameters van de ruwheidscoëfficiënt van Manning door 8 geomorfologen werd gebruikt.

2.3 Opmeten van rill- en ravijnerosie

Op het einde van het regenseizoen (eind augustus) werden de volumes van de gevormde rills opgemeten (lengte, breedte, diepte). Een GPS punt werd genomen voor ieder startpunt van een rill en gedigitaliseerd in GIS (ArcMap 10.1). Het bodemverlies door deze rillerosie werd berekend door het opgemeten volume rillerosie te vermenigvuldigen met de gemeten waardes voor bulkdensiteit voor ieder studiegebied. Daarnaast werd ook de kwetsbaarheid voor ravijnerosie van het land bestudeerd aan de hand van een gekoppelde criteria analyse, bestaande uit twee topografische parameters: de lokale helling van het oppervlak aan het ravijnhoofd en de oppervlakte van het gebied dat draineert naar het ravijnhoofd. Hiervoor werd de gestandaardiseerde procedure van de topografische drempelwaarde analyse toegepast, ontwikkeld door Torri & Poesen (2014). Topografische drempelwaardes worden meestal weergegeven op een dubbel-logaritmische schaal in de vorm van $s \geq kA^{-b}$, met s de helling van het oppervlak aan het ravijnhoofd, A de oppervlakte van het gebied dat draineert naar het ravijnhoofd en k en b gefitte parameters. De waarde voor k geeft de gevoeligheid van een gebied voor ravijnerosie weer. De waarde voor b wordt constant gehouden (b= 0.38 en b= 0.5) omdat deze geen trend vertoond voor verschillende landgebruikcategorieën. Vaak worden de drempelwaardes berekend voor de volgende landgebruikcategorieën: bos, akkerland en weiden. Vernieuwend aan de aanpak in deze studie is dat er een onderscheid gemaakt wordt voor verschillende land management technieken binnen de categorie ‘akkerland’. Hiervoor werden 26 bekkens afgebakend waar enkel *feses* werden gebruikt (*feses* bekkens), 27 bekkens waar enkel stone bunds werden gebruikt (stone bund bekkens) en 22 bekkens waar zowel *feses* als stone bunds werden gebruikt (gemengde bekkens) met een draagbare GPS. Een apart GPS punt werd genomen voor iedere gerelateerde stroomafwaarts gelegen ravijnhoofd. De lokale helling van het oppervlak aan het ravijnhoofd werd berekend met behulp van GIS in de pixel (30 m x 30 m) waarin het GPS punt van het ravijnhoofd lag. Bekkens waarin stone bunds aanwezig waren die na 2003 werden geconstrueerd, werden uit de dataset gehaald omdat het gerelateerde ravijnhoofd misschien gevormd werd onder een vorig land management. Het filteren van de data gebeurde met behulp van Google Earth waarin historische beelden van het studiegebied voor 2003, 2010 en soms 2013 terug te vinden zijn.

3. RESULTATEN

3.1 Karakteristieken van het studiegebied

Tijdens het regenseizoen van 2013 werd er in Wanzaye gemiddeld 372.35 mm neerslag opgemeten voor de periode van 15 tot 31 juli, 377.03 mm voor 1 tot 31 augustus en 66.02 mm voor 1 tot 4 september. De neerslag was homogeen verdeeld over het hele studiegebied. De *feses* densiteit varieerde over de tien sub-bekkens van 0 m per ha tot 510 m per ha met een gemiddelde van 254 m/ha (± 179 m/ha). In studiegebied 2 werden er geen *feses* gemaakt. De stone bund densiteit varieerde over de studiegebieden van 0 m/ha tot 626 m/ha, met een gemiddelde van 277 m/ha (± 232 m/ha). De studiegebieden waren gemiddeld 1.65 ha (± 1.2507 ha) groot. Het kleinste sub-bekken was 0.27 ha (studiegebied 10) en het grootste 4.21 ha (studiegebied 3). De volgende gewassen werden gecultiveerd in het studiegebied: millet, tef, tarwe, groene peper, ajuin, maïs, aardappelen en vlas, waarvan de eerste drie de meest voorkomende waren. Een gemiddelde bodemdiepte van 0.42 m en een gemiddelde oppervlakte stenigheid van 66.7% werden opgemeten in het studiegebied. De kleinste bulkdensiteit was gemeten in studiegebied 2 (1.31 g/cm^3) en de grootste in studiegebied 1 (1.74g/cm^3). Een gemiddelde bulk densiteit over het hele studiegebied van 1.56 g/cm^3 (± 0.11 g/cm^3) werd gevonden. Een Repeated Measures ANOVA test in SPSS toonde aan dat tijd geen significant effect had op het gravimetrisch vochtgehalte, waaruit we kunnen besluiten dat de antecedente bodemvochtcondities van de bodem gelijk waren. Er werd geen significante relatie gevonden tussen de bulkdensiteit en het bodemvochtgehalte. Een gemiddelde silt/klei ratio van 2.97 (±1.30) over het hele studiegebied werd gemeten, variërend van 1.43 (studiegebied 5) tot 5.52 (studiegebied 7).

3.2 Het gebruik van *feses*

Feses werden gemaakt met behulp van de *maresha* ploeg. Er werd een gemiddelde top breedte van 0.27 m (±0.09 m) en een gemiddelde diepte van 0.12 m (±0.02 m) opgemeten vlak na constructie. *Feses* werden gemaakt onder een hoek van gemiddeld 44.7° (± 7.2°) met de contourlijn. De gemiddelde *feses* gradiënt was 0.055 m/m (± 0.054 m/m). De grootste *feses* densiteit werd gevonden op akkerland waar groene peper en ajuin werd gecultiveerd (372 m/ha), gevolgd door tef (270 m/ha) en millet (236 m/ha). De laagste *feses* densiteit werd opgemeten voor telba (135 m/ha) en tarwe (158 m/ha). Een significante correlatie tussen *feses* densiteit en stone bund densiteit werd gevonden in Wanzaye (R= -0.72). Het was ook de enige variabele die significant werd gevonden voor de meervoudige lineaire regressieanalyse om de variatie in *feses* densiteit te analyseren: FD= 408.513 – 0.558 SB (R^2= 0.52), met FD = *feses* densiteit en SB = stone bund densiteit. Er werden twee mogelijkheden voor de evolutie van *feses* doorheen de tijd waargenomen aan de monitor sites: (1) sedimentatie van de *feses* (47%) en (2) degradatie van de *feses* (45%).

Interviews met landbouwers leverden interessante inzichten en belangrijke informatie op inzake het gebruik van *feses*. Landbouwers maken *feses* tijdens het zaaien en worden onderhouden tijdens het regenseizoen. *Feses* worden gemaakt voor de volgende redenen vermeld door de landbouwers in Wanzaye: (1) *feses* zijn vereist om het verlies van zaden door runoff vlak na inzaaiing te voorkomen, (2) *feses* worden gemaakt op steile gebieden om bodemerosie door ongecontroleerde oppervlaktestroom te beperken, en (3) *feses* worden gemaakt op zowel steile als vlakke gebieden om geaccumuleerd water te draineren. De laatste reden werd benadrukt als zijnde de belangrijkste door de meeste landbouwers. *Feses* worden gemaakt waar water van stroomopwaarts gelegen gebieden accumuleert, onafhankelijk van het gewas dat er gecultiveerd wordt, met een uitzondering voor groene peper en ajuin. De diepte van de *feses* wordt bepaald opdat de *feses* het jaar nadien kan weggeploegd worden met de *maresha*. *Feses* loodrecht op de contourlijn worden als mismanagement van het akkerland aanzien door de meeste landbouwers. Als er geen stone bunds aanwezig zijn, worden *feses* als de beste BWC aanzien, al zijn de meeste landbouwers ook op de hoogte van eventuele negatieve gevolgen van het gebruik van drainagekanalen (verdiepen *feses*, verlies van vruchtbare bodem). Stone bunds worden door de landbouwers in Wanzaye gezien als de beste BWC. Bijna alle landbouwers uitten de nood aan stone bunds voor hun akkerland, maar omdat het een tijdrovend werk is, zijn deze nog niet overal aanwezig. De meeste landbouwers bevestigden dat *feses* niet nodig zijn voor gebieden waar reeds stone bunds aanwezig zijn. Toch worden *feses* en stone bunds vaak samen gebruikt op akkerland, waarvoor landbouwers de volgende redenen gaven: (1) geen onderhoud van de stone bunds waardoor deze niet meer optimaal functioneren, (2) het overschot aan water moet weggevoerd worden, en (3) runoff dat over de stone bunds vloeit erodeert hun akkerland. Het beleid van de Ethiopische overheid luidt dat er geen *feses* gemaakt mogen worden in gebieden waar ook stone bunds aanwezig zijn, omdat deze de stone bunds kapot kunnen maken door de kracht dat achter het geconcentreerde water zit. Eventuele conflicten tussen landbouwers over het gebruik van *feses* worden in de meeste gevallen vreedzaam opgelost door tussenkomst van een lokale autoriteit, maar in de eerste plaats vermeden door het drainagekanaal naar een gemeenschappelijk pad te leiden.

3.3 De formule van Manning, runoff en runoff coëfficiënt

De ruwheidscoëfficiënt van Manning, berekend aan de hand van de geschatte parameters, varieerde van 0.043 (studiegebied 9) tot 0.123 (studiegebied 8) en het gemiddelde voor alle outlets van de studiegebieden is 0.068 (±0.123). Runoff werd berekend aan de hand van de routinemetingen aan de outlet van ieder bekken die werden omgevormd naar debieten door middel van de rating curves waarvan de waardes gebaseerd zijn op de formule van Manning. Een gemiddelde RC van 21.72% (±9.76%) over het hele studiegebied werd berekend en varieerde van 5.09% (studiegebied 2) tot 38.82% (studiegebied 3). Een multivariate regressieanalyse werd uitgevoerd met RC als afhankelijke variabele, maar geen enkele significante verklarende variabele werd gevonden. Een positieve correlatie met *feses* densiteit (R= 0.475) en een negatieve met stone bund densiteit (R= -0.176) werd gevonden, al zijn deze correlaties niet significant ($\alpha = 0.05$). Relaties tussen de RC en antecedente neerslag hadden een te lage correlatiecoëfficiënt, waarvoor werd besloten om deze relaties niet te gebruiken om de totale runoff te berekenen, inclusief voor periodes dat er geen routinemetingen werden uitgevoerd ('s nachts). Er werden geen significante relaties gevonden tussen de runoff coëfficiënt en het drainageoppervlak of de evolutie van het regenseizoen.

Hydrogrammen (debiet versus tijd) werden geconstrueerd voor ieder runoff evenement in elk studiegebied, waarvan de relaties tussen het maximum debiet (genormaliseerd door de drainage oppervlakte) en de kurtosis als afhankelijke variabelen en de *feses* densiteit en stone bund densiteit als onafhankelijke variabelen werden onderzocht. Piekdebieten nemen toe als de *feses* densiteit stijgt tot 300 m/ha, waarna het piekdebiet weer afneemt (tweedegraadsvergelijking). Piekdebieten nemen lineair af als de stone bund densiteit stijgt. Uit de data van Wanzaye kunnen we afleiden dat een hogere *feses* densiteit leidt tot een sterkere gepiekte hydrogram, terwijl voor een hogere stone bund densiteit het tegenovergestelde resultaat gevonden werd. Dezelfde tendensen werd gevonden voor het piekdebiet. Een relatie van de tweede graad was gevonden voor de kurtosis met *feses* densiteit als onafhankelijke variabele en een lineaire relatie met stone bund densiteit als onafhankelijke variabele.

3.4 Rillerosie

Het totale rill volume per ha (TRA) varieerde voor de tien studiegebieden van 0.17 m^3/ha (studiegebied 2) tot 13.19 m^3/ha (studiegebied 10). Het gemiddelde TRA over alle studiegebieden is 3.73 m^3/ha (± 4.20 m^3/ha) wat overeenkomt met een gemiddeld bodemverlies door rillerosie van 5.72 ton/ha (± 6.30 ton/ha). Rills gevormd door slecht geconstrueerde *feses* of stone bunds werden gecategoriseerd. Een slechte constructie impliceert *feses* die niet diep genoeg zijn of te lage stone bunds waardoor water uit/over de constructie stroomt en rillerosie creëert. Van alle gevormde rills werd 41% veroorzaakt door een slechte constructie van *feses* en 16% door een slechte constructie van stone bunds. Een positieve correlatie voor TRA met *feses* densiteit (R= 0.594) en een negatieve met stone bund densiteit (R= -0.498) werd gevonden, al zijn deze correlaties niet significant (α = 0.05). Een multivariate regressieanalyse werd uitgevoerd met TRA als afhankelijke variabele, waarvoor slechts één significante onafhankelijke variabele werd gevonden: TRA= -6.863 + 3.558SC (R^2= 0.635), met SC de silt/klei ratio.

3.5 Ravijnerosie

De afgebakende *feses* bekkens (verschillend van de 10 sub-bekkens) hadden een drainageoppervlakte van gemiddeld 0.45 ha (±0.20 ha), variërend van 0.15 ha tot 0.89 ha en een gemiddelde hellingsgradiënt van het oppervlak aan het ravijnhoofd van 0.29 m/m (±0.12 m/m). Stone bund bekkens hadden drainageoppervlaktes die varieerde tussen 0.31 ha en 2.75 ha met een gemiddelde van 1.24 ha (±0.78 ha) en een gemiddelde hellingsgradiënt van 0.33 m/m (±0.18 m/m). De geselecteerde gemengde bekkens hadden een gemiddelde drainageoppervlakte van 1.19 ha (±0.81 ha), variërend van 0.28 ha to 2.93 ha en een gemiddelde hellingsgradiënt van 0.21 m/m. (±0.13 m/m). De drainageoppervlakte van de *feses* bekkens was statistisch kleiner gevonden dan dat van de stone bund en gemengde bekkens. De hellingsgradiënt van het oppervlak aan het ravijnhoofd van de gemengde bekkens was statistisch kleiner dan dat van de *feses* en stone bund bekkens. k-waardes varieerde voor de drie land management strategieën. De kleinste waardes voor k werden gevonden voor *feses* bekkens. Hogere k-waardes werden gevonden voor gemengde bekkens, maar de grootste waardes voor k werden gevonden voor de stone bund bekkens. De gemiddelde k-waarde voor Wanzaye is 0.131 (±0,052) voor b= 0.38 en 0.123 (±0,054) voor b= 0.5.

4. DISCUSSIE

4.1 Bodem en topografische karakteristieken

De gemiddelde bulk densiteit gemeten in Wanzaye is relatief hoog. Dit kan liggen aan de volgende factoren: (1) de stalen werden enkel in akkerland genomen, (2) de zaaimethode waarbij vee wordt ingezet om het zaaibed voor te bereiden, en (3) het meerdere malen ploegen. De silt/klei ratio voor het studiegebied was relatief hoog, wat impliceert dat het gebied kwetsbaar is voor bodemerosie. Dit was onverwacht omdat het een kleirijke omgeving is, maar ook niet onmogelijk omdat zulke hoge waardes eerder ook al in het Tana bekken gevonden werden. De gemeten waardes en relaties tussen de bodemdiepte en helling liggen in lijn met eerdere onderzoeken voor gelijkaardige studiegebieden. Er werd gemiddeld een dunne bodem opgemeten die positief gecorreleerd is aan de gemiddelde helling van het bekken.

4.2 Het gebruik van *feses*

Van de metingen en interviews kunnen we afleiden dat het maken van drainagekanalen een moeilijke oefening is in het zoeken naar een balans tussen de voordelen (preventie erosie) en nadelen (oorzaak erosie) van het gebruik van drainagekanalen. Drainagekanalen verdiepen doorheen de tijd, al ging dit niet op voor alle drainagekanalen, waarvoor verder kwantitatief onderzoek wordt aanbevolen naar de evolutie van drainagekanalen doorheen de tijd. Er werden geen inherente elementen van het landschap gevonden om de variabiliteit in *feses* densiteit te verklaren, enkel een andere land management techniek (stone bunds) waarvoor we verder onderzoek op een grotere schaal aanbevelen. De sterke correlatie die werd gevonden tussen de stone bund densiteit en de *feses* densiteit kan worden verklaard door het overheidsbeleid dat het gebruik van *feses* verbied bij de aanwezigheid van stone bunds.

4.3 Meten van runoff debieten en de impact van land management op runoff

De veldmethode, gebaseerd op snelheidsmetingen van een drijvend object, kon slechts voor drie studiegebieden worden toegepast. Er werd geopteerd om voor alle studiegebieden de rating curve te maken aan de hand van de formule van Manning omdat de rating curves voor de drie studiegebieden aan de hand van de veldmethoden verschilden van die gebaseerd op de formule van Manning. Verschillen tussen de twee methodes kunnen te wijten zijn aan: onnauwkeurige metingen bij het toepassen van de veldmethode; de formule van Manning maakt een systematisch fout voor kanalen met een steile hellingsgradiënt; aanname van uniforme stroming in de outlet. De berekende runoff coëfficiënten (RC) voor studiegebieden 8 en 10 waren onrealistisch (minder neerslag dan runoff) wat mogelijks te wijten is aan (1) een onderschatting van de oppervlakte va het studiegebied dat draineert naar de outlet, (2) een systematische fout die gerelateerd is aan de zwakte van de formule van Manning voor kanalen met een grote hellingsgradiënt, (3) fout opgemeten hellingsgradiënten aan de outlets van de bekkens 8 en 10, en (4) foute metingen van debieten in bekkens 8 en 10.

De geschatte ruwheidscoëfficiënten van Manning voor de outlets van de tien studiegebieden in Wanzaye zijn gelijkaardig aan eerder gemeten waardes voor gelijkaardige studiegebieden. Toch zijn deze sterk verschillend van de gemeten ruwheidscoëfficiënten van Manning (te vergelijken voor studiegebieden 1,3 en 4). We raden verder onderzoek aan naar de toepassing van de formule van Manning voor het berekenen van debieten in gelijkaardige gebieden als die van Wanzaye. De gemiddelde RC ligt in lijn met de geschatte waarde van de RC voor het Tana bekken. Echter werd een hogere RC-waarde verwacht voor Wanzaye, omdat in onze studie enkel akkerland werd beschouwd. Maar, ook enkele andere lokale factoren zoals oppervlakte stenigheid, textuur, vegetatiebedekking, etc. beïnvloeden de RC. Bekkens met een hogere drainagedensiteit hebben sterker gepiekte runoff hydrogrammen. We raden verder onderzoek aan om een duidelijker beeld te krijgen over de relatie tussen het piekdebiet/ de piekheid van hydrogrammen en drainage densiteit.

4.4 De impact van land management op on-site rillerosie

Het TRA varieert sterk voor verschillende studies in het Ethiopisch hoogland. Dit komt omdat vele lokale factoren rillerosie beïnvloeden (oppervlakte stenigheid, BWC, neerslagparameters, etc.). TRA is relatief laag in Wanzaye door de hoge fractie oppervlakte stenigheid en de gebruikte BWC. Naast stone bunds wordt het gebruik van *feses* ook aanzien in Ethiopië als een goede manier om bodemerosie te vermijden. Toch konden we aan de hand van de data gemeten in Wanzaye de volgende trend afleiden: een hogere drainagedensiteit veroorzaakt een hogere TRA. Ook konden we afleiden dat een slecht onderhoud van de drainagekanalen leidt tot on-site erosie. Daarnaast werd ook bevestigd dat stone bunds een goede BWC is.

4.5 Lessen getrokken uit het gebruik van topografische drempelwaardes

Uit de analyse van de topografische drempelwaardes kunnen we 3 trends met betrekking tot land management afleiden: (1) het exclusieve gebruik van drainagekanalen wordt eerder toegepast op steilere hellingen waar slechts een klein drainageoppervlak nodig is om een ravijn te creëren, (2) stone bunds worden gebruikt op zowel steilere als gematigde hellingen waarop gewassen geteeld worden, en (3) bekkens met een gematigde helling en grote drainageoppervlaktes blijken tolerant te zijn voor het gecombineerde gebruik van stone bunds en drainagekanalen. Deze bevindingen komen overeen met wat landbouwers vertelden over het gebruik van BWC. Van de gevonden k-waardes kunnen we afleiden dat bekkens waarin exclusief drainagekanalen worden gebruikt het meest gevoelig zijn voor ravijnvorming in vergelijking met bekkens waar stone bunds aanwezig zijn. In vergelijking met andere studies over de rest van de wereld zijn de bekkens in Wanzaye niet zo gevoelig voor ravijnerosie.

5. BESLUIT

Uit de resultaten van de metingen in Wanzaye kunnen we de volgende conclusies trekken over het gebruik van drainagekanalen en stone bunds. Drainagekanalen leiden tot landdegradatie door de volgende processen: (1) aanzet tot on-site rillerosie, (2) geconcentreerde waterstroom dat leidt tot het verdiepen van het drainagekanaal en bodemtransport, en (3) geconcentreerde waterstroom dat leidt tot off-site ravijnvorming. Deze processen worden versterkt door de hogere piekdebieten en sterker gepiekte hydrogrammen bij een hogere drainagedensiteit. Toch heeft het gebruik van drainagekanalen ook de volgende voordelen: (1) het vermijden van het verlies van zaad vlak na het zaaien door runoff dat ongecontroleerd over het land stroomt, (2) het vermijden van erosie door runoff dat ongecontroleerd over het land stroomt, en (3) het wegvoeren van geaccumuleerd water. Stone bunds werden als een goede BWC bevonden. Drainagekanalen induceren een grote range aan effecten op het milieu waarvan niet alle effecten in deze dissertatie zijn besproken, waarvoor we verder onderzoek naar het gebruik van drainagekanalen op een grotere schaal van ruimte en tijd aanbevelen.

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1. INTRODUCTION[1]

1.1 Why research on surface drainage is required

As population densities are rising, more pressure is put on the land, and even steep sloping areas are cultivated (Turkelboom *et al*., 2008; Smit & Tefera, 2011; Mekuria *et al*., 2012; Haile & Fetene, 2012). In regions where soils have poor internal drainage and where rainfall depth exceeds evapotranspiration depth during the rainy season, nearly all sloping farmlands require drainage for crop production. Although drainage has a wide range of benefits, in many cases, the establishment of drainage ditches is perceived as a major mismanagement of farmland that leads to on-site and off-site land degradation (Smit & Tefera, 2011; Simane *et al*., 2013; Zhang *et al*., 2013). The environmental impacts of land surface drainage cannot be simply and clearly stated. For instance, Pathak *et al*. (2005) and Turkelboom *et al*. (2008) report that drainage ditches on steep slopes can control gully erosion by diverting the water away from the gully head, whereas other studies point to drainage ditches as triggers of gullies (Archibold *et al*., 2003; Ireland *et al*., 1939; Smit & Tefera, 2011; Zhang *et al*. 2013). Because gully erosion is the worst stage of soil erosion by water and a worldwide problem (Poesen *et al*., 2003; Valentin *et al*., 2005), a comprehensive analysis on the hydrological effects of man-made drainage ditches is required.

A review is made of the effects of drainage ditches on sloping farmland with a focus on drainage ditch systems as a factor initiating rill and gully erosion. First, we consider seasonal soil saturation as a trigger for runoff production (Archibold *et al*., 2003). As overland flow leads to soil erosion on farmlands and loss of crop yield (Tilahun *et al*., 2013; Ngatcha *et al*., 2011; Singh & Agnihotri, 1987), the use of drainage ditches and their positive effects for crop production are introduced in the next section. Next, the negative effects of enhanced drainage are presented at different scales. Off-site effects such as gully formation (Burkard & Kostachuk, 1995; Turkelboom *et al*., 2008) and increased peak discharge (Holden *et al*., 2004; Skaggs *et al*., 1994) are taken into account, followed by the on-site effects (Tebebu *et al*., 2010; Shiferaw, 2002). Besides these drainage ditches, we discuss thereafter the naturally formed ephemeral gullies (EGs) that show some similarities with human-made drainage ditches (Bewket & Sterk, 2003; Zhang *et al*., 2007) and consider the spatial and social

[1] This was published as: Monsieurs, E., Dessie, M., Adgo, E., Poesen, J., Deckers, J., Verhoest, N., Nyssen, J. 2014. Seasonal surface drainage of sloping farmland and its hydrogeomorphic impacts. Land Degrad. Dev. DOI: 10.1002/ldr.2286. IF=1.991; Ranking: 2012: 10/34 (Soil Science); 92/210 (Environmental Sciences)

dimensions of these effects of drainage ditches. What follows are the measurements and discussion on the use of drainage ditches and stone bunds in the Lake Tana Basin (Ethiopia) to give insight into the hydrological effects of man-made drainage ditches and to illustrate the importance and the need for further research on the hydrogeomorphic effects of drainage ditches. This research fits in a project called "Water and sediment budget of Lake Tana for optimization of land management and water allocation" (WASE-TANA).

1.2 Rainfed farming and water management

1.2.1 Seasonal soil saturation and runoff

The occurrence of surface runoff has been schematically illustrated by Steenhuis *et al*. (2009) and Bayabil *et al*. (2010) who divide basins in the hill slopes and the lower, relatively flatter areas. Precipitation on the hill slopes can partly infiltrate and partly flow downslope as (sub-) surface flow. Areas in the landscape where run-on and rain depth are greater than runoff and infiltration become saturated during the rainy season. The differences in flow discharge along the slope are due to differences in slope gradient, concavity of the area, depth to an impermeable layer in the soil (Bayabil *et al*., 2010), transmissivity (James & Roulet, 2009) and rainfall characteristics (Ziadat & Taimeh, 2013). Surface runoff is generated by a variety of processes, which are summarized by Ponce & Hawkins (1996):

1. Hortonian overland flow
2. Saturation overland flow
3. Surface phenomena (crust development, hydrophobic soil layers…)
4. Throughflow processes
5. Partial-area runoff
6. Direct channel interception

The difference between Hortonian and Saturation overland flow is that the former takes place when rainfall exceeds infiltration rate and the latter when the soil is saturated. In both conditions, infiltration capacity is low as it is for the "Surface phenomena". "Throughflow processes" includes subsurface runoff on a less permeable layer. "Partial-area" is a concept where only a part of the catchment, though a consistent part, contributes to runoff. Interception by channels refers to the runoff originating from rainfall falling directly into the channels. This can be important in dense channel networks. Research on infiltration and rainfall depth by Ashagre (2009) show that infiltration rates in Ethiopia are equal to or higher than the rainfall intensity.

Saturation of the soil and jointly its effect on surface runoff is often seasonally bound. Tilahun *et al.* (2013), Ngatcha *et al.* (2011) and Singh & Agnihotri (1987) amongst others studied the erosive effects of overland flow due to soil saturation during the rainy season in Ethiopia, Cameroon and India respectively. Concentrated overland flow is the main factor of gully erosion on cropland (Govers *et al.*, 1990; Auzet *et al.*, 1993). Due to soil saturation, more runoff water is produced that is captured by the drainage ditch system. Higher discharges lead to a larger erosive force of the flows in the downstream gullies (Archibold *et al.*, 2003). Shallow soils, if occurring in the middle and lower parts of the slopes, get saturated more quickly and hence rill and gully initiation is more likely in these areas (Zhang *et al.*, 2007; Steenhuis *et al.*, 2009; Bewket & Sterk, 2003).

1.2.2 Drainage of sloping farmland

The aim of digging drainage ditches on cropland is to reduce the negative effects of excess of water on crops. The primary objective of a drainage system on sloping land is to capture the temporary excess of water and evacuate it downhill. Artificial drainage of the land aims at securing an unsaturated top soil layer and hence (1) reduce the damage from scalding due to the detrimental effect of ponding water in hot areas (Luthin, 1966), (2) prevent soil compaction as a result of animal trampling on saturated soil, (3) support crop germination as drained soils are warmer, (4) prevent subsurface anoxic conditions (waterlogging), (5) enhance the water holding capacity, (6) increase aeration, (7) lead to more uniform crop growth, (8) allow a greater variety of crops, (9) lead to a deeper root zone, (10) protect plants from disease and (11) decrease the mechanical power needed for tillage operations (Luthin, 1966; Robinson, 1990; Spaling & Smit, 1995; Zhang *et al.*, 2013).

In contrast to level areas where drainage ditches mainly aim at lowering the level of the phreatic surface when it comes near or at the surface (Schot *et al.*, 2004; Qureshi *et al.*, 2013), digging ditches to divert runoff water on sloping cropland is a physical soil conservation practice to protect the land from uncontrolled runoff and hence decrease the risk of topsoil and seedling erosion. It is also used to control gully erosion by diverting runoff water away from active gully heads (Pathak *et al.*, 2005; Shiferaw, 2002). Such structures that intercept overland flow and divert it laterally to a supposedly safe and well established drainage channel are called *cut-off drain*, *diversion ditch* (Turkelboom *et al.,* 2008), *slanted drain* or locally in Ethiopia *tekebekeb* (Shiferaw, 2002) or *feses* (Monsieurs *et al.,* 2014).

In the Roujan basin in France, drainage ditches are 0.7 to 1.2 m wide and 0.8 to 1.4 m deep (Moussa *et al.,* 2002). Million (1996) found in his study in North Shewa highlands in Ethiopia drainage ditches of which the width varied from 30 to 50 cm and depth from 5 to 25 cm. In northern Thailand and Ethiopia, Turkelboom *et al.* (2008) and Shiferaw (2002) concluded that the widths of the drainage ditches are very variable and mostly determined by the width of the tillage tool. The depth of the drainage ditch depends often on the soil depth. The gradient of ditches varied considerably from farmer to farmer from 3 to 20% (Million, 1996). Turkelboom *et al.* (2008) found drainage ditches with gradients of 15-50%. In developing countries, decisions on the dimensions of the ditch establishment variables (width, depth, gradient) are based on indigenous knowledge of local conditions and empirical observations. Although some studies mention dimensions of drainage ditches as discussed above, there is a scarcity of literature about the explanatory factors of drainage densities on sloping farmland and about quantities of soil loss associated with the use of drainage ditches.

The main two categories of man-made drainage systems are (1) subsurface drains and (2) surface drains. Subsurface drainage systems are situated beneath the soil, so the land can be farmed over the drain. Their initial cost is however high (Luthin, 1966). Different surface drainage ditch systems can be distinguished on sloping lands, where they are often ephemeral as they are destroyed during preparatory tillage of the land and shaped again (by hoe or plough) after crop emergence in the period when overland flow starts to occur (Shiferaw, 2002; Million, 1996). *The cross-slope ditch system* or *interception system* consists of ditches at the lower end of the slope. Water from the farmland is captured by open collector ditches, running at a slight angle with the contour. The *random-ditch system* is applied in fields where random depressions exist which are too deep to fill by land smoothing. The ditches will connect these depressions to transport the excess of water downslope. *Surface-drainage bedding system* is an old drainage practice. Beds are formed in the farmland and separated by parallel open field ditches (Luthin, 1966). These ditches are oriented towards the greatest land slope. Typical examples of such land surface drainage techniques are the Camber bed drainage in for example Ghana (Nyalemegbe *et al*., 2010) and Ethiopia (Srivastava *et al.*,

1993) or the broad-bed-and furrow (Astatke *et al.*, 2002; Morrison *et al.*, 1990) both of which have been promoted with variable degrees of success (Gebreegziabher *et al.* 2009). A collector drain at the lower end of the field gathers all the drained water. *Parallel-ditch system* can be used on flat, poorly drained soils. The land between the parallel ditches is smoothed, so the overland flow encounters no obstruction. For all of the above systems, the cross-sections of the ditches are trapezoidal or V-shaped if they are smaller (Luthin, 1966).

1.2.3 Drainage ditches and downstream hydrogeomorphic responses

The use of drainage ditches has an impact on the farmland itself and on the downstream area (Table 1). Drainage ditches may cause hydrogeomorphic changes because of their repetitive and expansive nature (Spaling & Smit, 1995). For example, drainage is frequently associated with a reduction in wetlands or changes in stream discharge (Figure 1). Those changes can be positive as already discussed, or negative: the establishment of drainage ditches is increasingly recognized as a major factor of off-site environmental impact, as it increases sediment load, peak runoff rate and thus increasing flooding problems downstream (Skaggs *et al.*,1994).

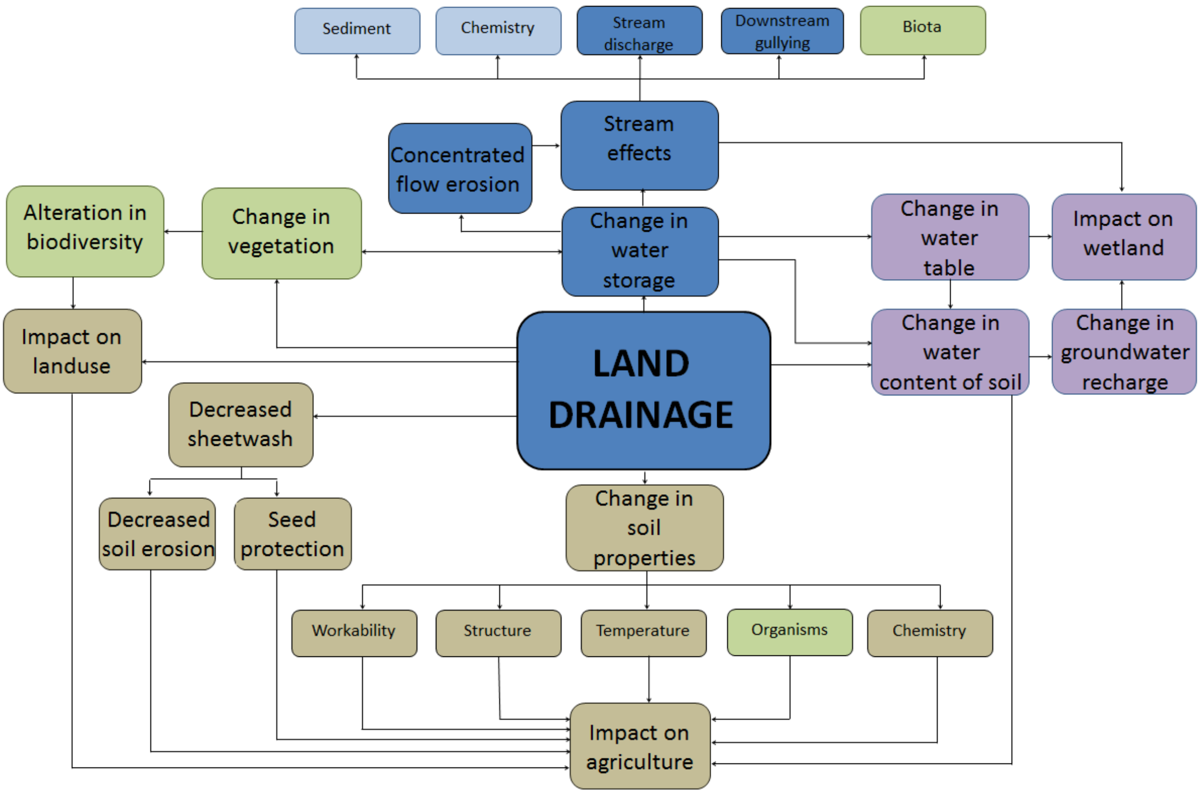


Figure 1. Environmental changes induced by drainage ditch construction; in brown colour changes linked to agriculture, in green to vegetation and biodiversity, in purple to groundwater, and in blue to surface water. Changes addressed in this study are in dark blue (modified from Spaling and Smit, 1995).

Table 1. Studies addressing seasonal surface drainage ditches on cropland and their hydrogeomorphic effects. Study areas are listed by latitude; NA = not available (Monsieurs *et al.*, 2014).

Country	Place	Rain and runoff regime	Slope gradient (%)	Soil type	Hydrogeomorphic impacts: Downstream: Gully formation	Downstream: Increased peak discharge	On-site: Gully formation	Links with ephemeral gullies	Social and spatial aspects	Authors
Canada	Saskatoon, Saskatchewan	Seasonal	NA	Relatively impermeable clays	+					Archibold *et al.* (2003)
Canada	Goderich	Peak discharges during spring melt	NA	NA	+	+				Burkard & Kostachuk (1995)
Canada	Southern Ontario	Extreme precipitation regimes in summer	NA	Various					+	Spaling & Smit (1995)
The Netherlands	Central Netherlands	Precipitation surplus of 200–400 mm y^{-1}	NA	Peat, clay						Schot *et al.* (2004)
France	Roujan Basin	Bimodal	2–24	Calcaric soils						Hebrard *et al.* (2006); Moussa *et al.* (2002)
Spain	Southern Navarra	High interannual variability	1–14	Loam	+	+		+		Casali *et al.* (1999)
USA	Washington	Spring snowmelt	Various	NA	+	+	+			Veldhuisen & Russel (1999)
USA	Piedmont, South Carolina	Various	NA	Various	+	+				Ireland *et al.* (1939)
Thailand	Pakha village, Mae Chan District	Seasonal	11–84	Umbrisols, Regosols, Cambisols	+		+			Turkelboom *et al.* (2008)
Southeast Asia		Monsoon climate	NA	Various	+					Sidle *et al.* (2006)
Ethiopia	Choke Mountains	Seasonal	5–25	Heavy clay	+		+		+	Smit & Tefera (2011); Simane *et al.* (2013)
Ethiopia	Gozamen, East Gojjam	Unimodal rainfall pattern	NA	Only local names are given	+		+		+	Shiferaw (2002)
Nigeria	Imo State	Heavy rainfalls	NA	NA	+		+			Hudec *et al.* (2005)
Ghana	Accra Plain	Two rainy seasons	0·1–1	Vertisol						Nyalemegbe *et al.* (2010)
Australia	NRCMA region	Various	NA	Various	+	+	+		+	Alt *et al.* (2009)
Various	Various	Various	NA	Peat		+	+			Holden *et al.* (2004)
Various	Various	Various	Various	Various	+					Pathak *et al.* (2005); Luthin (1966); Simon & Rinaldi (2006); Skaggs *et al.* (1994)

1.2.3.1 Gully formation

The erosive force of the concentrated water flow in the drainage ditches may initiate downslope gullying of valley bottoms and further incision of existing waterways (Ireland *et al.,* 1939; Simane *et al.*, 2013). Farmlands with significant surface run-on may suffer from gully development as observed in the highlands of northern Thailand. Human-made linear landscape features such as diversion ditches or footpaths are most important for runoff concentration, rapid transmission of peak flows to the lower part of the catchment, and hence gully development (Turkelboom *et al.,* 2008). Burkard & Kostachuk (1995) studied gullies in glacial clays in Ontario and observed gully expansion resulting from alteration of surface drainage patterns by agricultural drainage ditches. Archibold *et al.* (2003) reported similar observations in a catchment in Saskatoon (Canada) where snowmelt is the most prominent source of soil moisture and surface runoff. When the soils are saturated, infiltration capacity is too low and more water is concentrated into the drainage ditch system, which drains into valley bottoms, gullies and first order streams. Lack of cooperation between land users upstream for safe drainage and gully protection may hence lead to severe downstream gully erosion (Smit & Tefera, 2011). Zhang *et al.* (2013) and Simane *et al.* (2013) emphasize the importance of a well-thought drainage ditch design in order to benefit from the positive effects resulting from drainage ditches, while reducing the downstream effects. A poorly planned drainage ditch layout leads to enhanced gully erosion downstream (Simane *et al.*, 2013) and causes higher peak runoff discharge, with concomitant losses of soil and nutrients (Zhang *et al.*, 2013).

1.2.3.2 Increased peak discharges

The peak discharge in rivers will be larger where hill slopes have a high drainage density. The drainage density comprises both drainage ditches and natural drainage by gully channels (Holden, 2004; Skaggs *et al.,* 1994). Turkelboom *et al.* (2008) found that gully development is closely related to the runoff-generating areas, runoff-concentrating features, and connective elements within the catchment. Drainage ditches increase the runoff connectivity in the catchment (Sidle *et al*., 2006). The presence of a drainage network is one of the most critical characteristics to identify farmlands that cause off-site problems (Turkelboom *et al.,* 2008). But Trafford (1973) and Thomasson (1975) downplay the effect of drainage ditches on peak discharges: drainage of permeable soils generally results in a lowering of the flow peaks. The concept here is that the drainage ditches lower the temporary water table (induced by seasonal rainfall) and hence increase the temporary storage capacity of the top soil layer (Thomasson, 1975). This results in a larger capacity of the soil to absorb the rain that falls during the beginning of each event.

1.2.4 Drainage ditches and on-site gully initiation

1.2.4.1 Gully formation

The concentrated water flow in the surface drainage ditch system may also generate on-site effects on the farmland. There is scarcity of literature on this topic although problems of on-site gully initiation are widespread. In western Washington (USA) (Veldhuisen & Russel, 1999) and on the steep and wet highlands of northern Thailand (Turkelboom *et al.,* 2008) drainage ditch failures were observed when ditches got clogged by sediment. Runoff could break through the ditch wall, divert the water out of the drainage ditch and create a rill or a gully. The lack of maintenance of physical structures such as stone bunds (*sensu* Nyssen *et al*., 2007) or drainage ditches reduces their effectiveness and even allows concentrated flow which enhances gully development (Tebebu *et al.*, 2010; Shiferaw, 2002). At smallholder level, particularly in complex terrain, creating an effective drainage ditch system requires experience, (indigenous) knowledge of soils, and skills, as too steep ditches enhance incision and gully formation, too shallow ditches create overflow of the ditches and rill formation, and too many ditches are time- and space-consuming (Smit & Tefera, 2011). Poor design and obstruction of the drains are major causes of gully initiation (Hudec *et al.,* 2005; Alt *et al.,* 2009; Smit & Tefera, 2011).

Holden *et al.* (2004) studied the impact of peat drainage and concluded that wetland soils suffer from severe degradation due to ditches which can quickly erode deeply. Incised drainage ditches allow higher peak flows and are very dynamic whilst they dissipate little flow energy (Simon & Rinaldi, 2006). Ditch degradation and widening over time are the undesirable effects (Alt *et al.,* 2009; Simon & Rinaldi, 2006) (Figure 2). To avoid ditches developing into gullies, farmers will yearly change their position (Shiferaw, 2002; Million 1996). Ireland *et al.* (1939) characterize gully forms of which some are determined by drainage ditches (Figure 3), particularly, the *linear* form is common along parcel borders following old or existing drainage ditches, and the *parallel* system can be formed out of parallel ditches.

Figure 2. Slightly slanted drainage ditches on cropland drain surface runoff towards a main drainage ditch running downslope (diagonally through the photograph) and hence induce gully erosion. Direction of flow in the drainage ditches is indicated by arrows. Farmers make use of both drainage ditches and stone bunds (Wanzaye, Ethiopia, Aug. 2013).

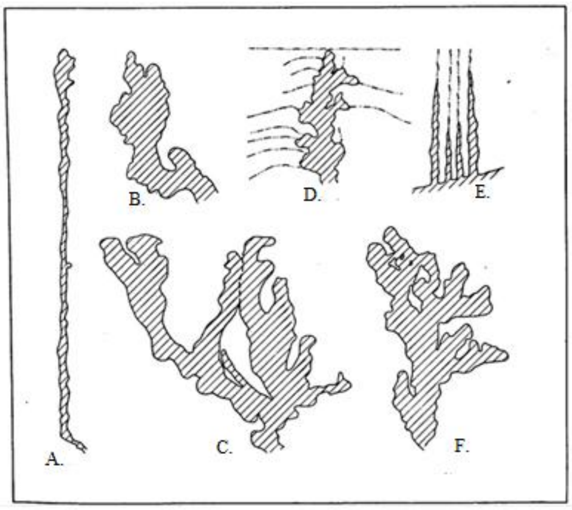


Figure 3. Characteristic gully forms in relation to surface drainage: A. linear; B. bulbous; C. dendritic; D. trellis; E. parallel; F. compound (after Ireland *et al.,* 1939).

1.2.4.2 Other on-site effects

Substantial on-site soil losses to the underground drainage system have also been observed in a catchment in Ullensaker (Norway). This subsurface soil loss was accelerated by the soil saturation at the end of a snowmelt period (Oygarden *et al.*, 1997). Another possible on-site effect of the establishment of drainage ditches is moisture deficit at the end of the rainy season. Hebrard *et al.* (2006) emphasize the large influence of land management such as drainage ditch networks on soil moisture distribution in a catchment. Nevertheless, literature is very scarce on the specific causal relation between drainage ditches and moisture stress for crops at the end of the rainy season.

1.2.5 Interactions and similarities between drainage ditches and ephemeral gullies

Besides man-made drainage ditches, also the effects of natural drainage on hydrogeomorphology can be considered. The hydrological processes associated with ditches were also observed with ephemeral gullies (Poesen & Hooke, 1997), i.e. clearly formed natural waterways mostly reoccurring at the same place (Foster, 1986). Swiechowicz (2011) showed that ephemeral gullies on cultivated areas in Poland are most frequently formed on cultivated slopes in natural drainage lines. Studies conducted in the Mediterranean area (Martinez-Casasnovas *et al.,* 2005), China (Zhang *et al.*, 2007) and in Ethiopia (Bewket & Sterk, 2003; Tebebu *et al,* 2010) confirm the findings of ephemeral gully (EG) formation on cultivated land, which constitutes the main drainage system. Casali *et al.* (1999) studied ephemeral gully erosion in Spain by which three main types of EG are distinguished: (1) classical EG, (2) drainage EG and (3) discontinuous EG. The drainage EGs were formed by flows from drainage ditches in upstream farmlands which erode the cultivated plots downstream. They found that drainage EG were the most active EG and hence eroded the largest volume of soil. Also in Ethiopia, we observed that many ephemeral gullies are fed by runoff water from slanted drainage ditches, although there is a lack of research about this topic. According to Tebebu *et al.* (2010) and Easton *et al.* (2010), gullies grow more easily on saturated soils because of positive pore water pressures reducing the shear strength of the soils. Overland flow is the main factor of gully erosion on cropland (Govers *et al.,* 1990; Auzet *et al.,* 1993). Fields in midslope positions are more susceptible for rill erosion because of the runoff concentration (Bewket & Sterk, 2003).

When EG are not controlled by tillage operations, they can grow into large gullies (Woodward, 1999; Bennett *et al.,* 2000; Le Roux & Sumner, 2012). Tillage-induced roughness can redirect runoff water from topographically determined directions of flow to tillage lines. This concentrated flow can initiate uncontrolled EG (Takken *et al.*, 2001). Long-term productivity of the farmland declines because of the repeated removal of top soil by gully erosion followed by the filling operations (Poesen *et al*., 2006; Yitbarek *et al.,* 2012).

Another effect of this process is the gradual lowering of the soil surface (Woodward, 1999; Burkard & Kostachuk, 1995; Valentin *et al.*, 2005). The most documented on-site effects of water erosion and surface runoff include nutrient and soil losses (Poesen & Hooke, 1997; Steegen *et al.*, 2001; Martinez-Casasnovas *et al.*, 2005). All these effects of EG are also applicable to ephemeral drainage ditches that are created yearly in farmers' fields in different but nearby and parallel positions.

1.2.6 Drainage and gullying in relation to social and upstream-downstream power conflicts

The history of the conflict concerning the effects of man-made hillslope drainage in England has been summarized by Robinson (1990). Severe floods of the Thames (London), Severn (Wales) and other large rivers in England were claimed as being the inevitable result of upstream drainage of farmland. The divided academic opinion about the effects of drainage ditches caused governmental inconstancy. For many years the government has been giving public money to farmers for the establishment of drainage ditches, whereas they recognized that further research of the hydrological effect of agricultural drainage is required. The study of Bankoff (2013) indicates that this discussion in England is still of interest today. Similarly, drainage of peatlands has worldwide been the subject of conflict between different stakeholders such as nature conservationists, and economists who want to increase farmland productivity (FAO, 2012; Koivusalo *et al.*, 2008). Wetland loss by peat drainage has severe consequences for local populations in Africa depending on the source of water and nutrients required for biological productivity. However, decision-makers often perceive wetlands to have little value compared to drained wetlands with more visible and immediate economic benefits (Schuyt, 2005). Also in Scotland, the relationship between peatland soils and man induced drainage has gained attention (Bragg, 2002).

Smit & Tefera (2011) investigated the reason why gully erosion is still present on a hill slope of the Choke Mountain (Ethiopia) despite more than 20 years of soil conservation programs. They concluded that land degradation is not caused by intensive cultivation but by the absence of a coordinated drainage ditch system, that results from the occurring social relations within the community. Larger landowners have a higher status and are put in a favorable position when disputes arise concerning land, irrigation water or other 'public goods' distribution. This makes them privileged to construct drainage ditches which may benefit their crop yield but are detrimental for their downslope neighbors. Different interests, different social and topographical positions make it hard to establish a cooperation between land users to stop gully formation.

Farmers try to construct their drainage ditches in such way that they will end up in a stream, forest or a fallow land which can slow down the runoff velocity and trap the transported sediment (Turkelboom *et al.*, 2008). However, Shiferaw (2002) points to the major limitation of drainage ditches in a watershed in East Gojjam (Ethiopia): the ditches are constructed in order to find the best way to drain the excess of water so that they may have to cross croplands belonging to different farmers. These drainage ditches hence form a potential source of conflict between neighboring farmers.

Case studies on drainage ditches (Smit & Tefera, 2011; Shiferaw, 2002; Turkelboom *et al*., 2008) confirm the theory of Lanckriet *et al.* (2014) following Blaikie *et al.* (1994), who state that traditional crop producers in the third world are not in a chronic crisis but the economic impoverishment is caused by human interactions with nature. Despite the land degradation factors often put forward in literature, Lanckriet *et al.* (2014) emphasisethe political mode of production (traditional subsistence, power relations, civil war, post-war) and its related conservation strategies.

1.2.7 Drainage in Lake Tana basin

The rainfall pattern in the Lake Tana basin has an important impact on crop cultivation. The growing season for the Lake Tana region is limited to the duration of the rainy season and a subsequent period with residual moisture (Colot, 2012). Rainfed farming agriculture is dominant in the Lake Tana basin, as it is in most parts of Ethiopia (Colot, 2012; Araya *et al*., 2012; Hurni *et al*., 2005). Farmers usually wait until a considerable amount of rainfall has fallen before planting. This way, they try to avoid crop failure but in turn, bring about inadequate moisture supplies during the flowering stage and hence minimum grain yield (Gebreegziabher *et al*., 2009).

Traditional drainage ditches in humid and sub-humid regions of Ethiopia are dug on hillslopes during the rainy season. These ditches are locally known as *feses*. *Feses* are established using the *maresha* ard plough, drawn by a pair of oxen (Gebreegziabher *et al*., 2009). Farmers alternate the position of the traditional constructed ditches every cropping season in order to avoid their gradual widening and deepening over time (Shiferaw, 2002). Farmers are aware of the fact that drainage ditches transport fertile topsoil from their land downstream. But according to the farmers in Lake Tana basin *feses* are the best way to avoid soil erosion in the beginning of the rainy season if no other on-site conservation measures like stone bunds are available. As a result of this soil transport, the bottom of the *feses* frequently reaches down to the bedrock (Figure 4) (Monsieurs *et al.,* 2014).

Figure 4. Bedrock exposure by gully erosion due to the construction of a *feses* in cropland near Wanzaye (Aug. 2013). In the background, another gully has cut the soil down to the bedrock.

1.3 Problem statement

Soil loss due to water erosion is a severe threat to the subsistence rainfed agriculture and the national economy of Ethiopia (Bewket & Sterk, 2003, Poesen *et al*., 2003; Tebebu *et al*., 2010). With the actual rate of soil loss on the slopes of the Ethiopian Highlands, the thin soil mantle will be removed in less than two centuries (Bewket & Sterk, 2003). Loss of rainwater is another concerning problem. Rainfed farming is limited by the scarcity and unreliability of annual rainfall and losses by surface runoff (Araya & Stroosnijder, 2010). Researchers are still divided about the balance of their positive and negative effects (Monsieurs *et al.,* 2014). Also in the Lake Tana basin, farmers are aware of both positive and negative effects of the establishment of drainage ditches.

Rill erosion and gully formation are the most important processes causing soil loss by water which form a severe threat to the subsistence rainfed agriculture and the national economy of Ethiopia. Thus the lack of knowledge of (1) the process of gully erosion (Poesen *et al.*, 2003; Tebebu *et al*, 2010) and (2) the environmental impacts of artificial drainage (Skaggs *et al.*, 1994) is problematic as it can lead to mismanagement in the basin. This concerns also the livelihoods of tens of millions of people downstream in the lower Nile river basin.

1.4 Research objectives

With regard to the use of different farming systems (farmers' drainage system, crops used, soil and water conservation, parcel size), this study will focus on their impact on the different hydrological processes (runoff response, gully development, etc.). This study will specially focus on the hydrogeomorphic impacts of drainage ditches. Conclusions will contribute to management strategies to reduce their negative environmental impacts.

The specific research objectives are:
-Finding explanatory factors for the establishment and use of drainage ditches.
-Analyzing the on-site and off-site hydrogeomorphic impact of the use of drainage ditches.
-Assessing cropland vulnerability to soil erosion in relation to a specific land management.

1.5 Research questions and hypotheses

To measure the impacts of the farming systems on the different hydrological processes, the other variables of the catchment which influence the hydrological processes need to be kept constant as much as possible. Such variables are: slope gradient, land use and soil type (Polyakov *et al.*, 2010; Osborn & Lane, 1969). The input for the catchments is rainfall depth. The hydrogeomorphological processes are the output of the catchment (runoff and rill/gully formation) (Figure 5).

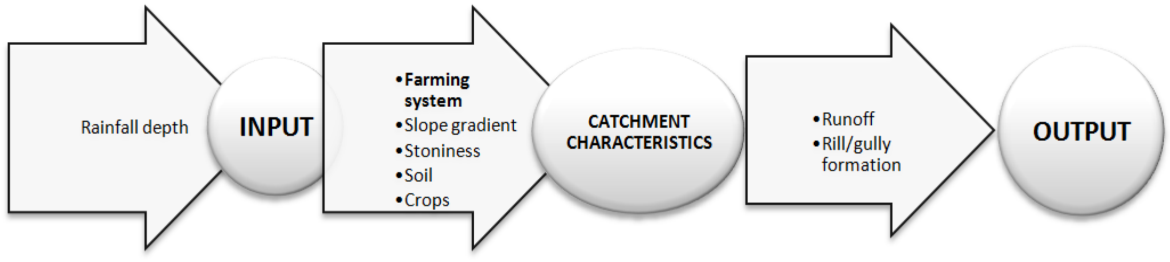


Figure 5. Research design.

1.5.1 Research questions

To focus on the farming system variables, the following questions will be taken into account. (I.1) Which drainage system is used? (I.2) Which crops are used? (I.3) Is any kind of soil and water conservation present? Besides spatial variations (above) the hydrological impacts of these farming practices will be examined. (II.1) How much rain falls on the land? (II.2) What is the evolution of the soil moisture content? (II.3) What is the runoff response? (II.4) Do rill and gully formation appear? (II.5) What is the amount of soil loss? (II.7) How does the drainage system interact with hydrological processes as well as with other soil degradation processes?

1.5.2 Research hypotheses

The research questions above will enhance to put the different land management practices (stone bunds, drainage ditches) in a broader context. Taking into account studies done in other parts of the Ethiopian Highlands, some hypotheses can be formulated with a focus on the effect of the use of drainage ditches.

Gully initiation is attributed to insufficient channel capacity of the drain (Alt *et al*., 2009) or obstruction of the drain (Veldhuisen & Russel, 1999). The result is an unregulated water flow which enhances the rapid development of gullies (Hudec *et al*., 2005).

Hypothesis 1: Poor drainage management (channel capacity, obstructions) will enhance on-site erosion.

Incised drainage channels can contain higher peak flows and are very dynamic whilst they dissipate little flow energy (Simon & Rinaldi, 2006). Channel degradation over time is the undesirable effects (Alt *et al*., 2009; Simon & Rinaldi, 2006).

Hypothesis 2: Drainage channels will incise over time.

Drainage and gullies cause a higher peak runoff (Holden, 2004; Skaggs, 1994) and hence, higher erosion rates (Hooke, 1979).

Hypothesis 3: Peak runoff will be higher where hill slopes have a high drainage density. The drainage density comprises both artificial drainage ditches as natural drainage by gullies.

Drainage has an important off-site environmental impact. It will concentrate the water within the catchment, which creates an erosive force to create gullies downstream. (Ireland *et al*., 1939; Burkard & Kostachuk, 1995; Archibold *et al*., 2003; Smit & Tefera, 2011)

Hypothesis 4: Drainage systems in upstream fields will contribute to gully erosion downstream.

Measurements on runoff are variable during the crop growing period. Runoff decreases due to increasing vegetation cover. (Steenhuis *et al*., 2009; Easton *et al*., 2010; Gebreegziabher *et al*., 2009; Descheemaeker *et al*., 2006; Girmay *et al*., 2009; Vanmaercke *et al.*, 2010)

Hypothesis 5: Runoff decreases during the growing season.

The size of the catchment is a variable to take into account when measuring runoff. Studies have found a relation between catchment size and runoff: runoff decreases with increasing catchment area (Nyssen *et al*., 2010).

Hypothesis 6: Runoff decreases with increasing catchment area.

Stone bunds on farmland cause a higher soil and water retention according studies from Gebremichael *et al*. (2005) and Nyssen *et al*. (2011) in the Northern Ethiopian Highlands. This has been confirmed by recent studies in the Gumara-Maksegnit sub-basin in the Lake Tana Basin (Brenner *et al*., 2013). However, the effect of the stone bunds on crop production is concentrated along the bunds.

Hypothesis 7: Stone bunds are efficient tools for soil and water retention.

2. METHODS AND MATERIALS

2.1 Study area

2.1.1 The Ethiopian Highlands and Lake Tana basin

Numerous studies in the Ethiopian Highlands characterize them as a fragile environment. High population pressure, poverty, international unequal development, poor land use practices, natural conditions, land use change and improper management systems have played a role for causing land degradation problems in the Ethiopian Highlands. This land degradation leads to a higher rate of surface runoff and sediment transport from the Ethiopian Highlands (Rientjes *et al*., 2011; Awulachew *et al*., 2008; Hurni *et al*., 2005; Nyssen *et al*., 2004; Meshesha *et al*., 2012; Setegn *et al*., 2009; Descheemaeker *et al*., 2006; Vanmaercke *et al*., 2010; Erkossa *et al*., 2005; Tesfaye & Walker, 2004). The "natural conditions" leading to land degradation in the Ethiopian Highlands include intense rainfall, the occurrence of flash floods, steep slopes and vertisols. Productivity from these soils is limited by erosion due to their physical properties (Moeyersons *et al*., 2006; McHugh *et al*., 2007). As an inevitable consequence the sustainability of traditional agricultural systems is threatened. Nyssen (2004) noted applicably: "Human impact is important, not only as a factor of degradation, but also as a factor of environmental recovery".

Despite the land degradation factors often put forward in literature as mentioned above, Lanckriet *et al*., (2014) emphasises the political mode of production and its related conservation strategies. Under feudalism, until 1974, land conservation in Ethiopia was largely neglected. Most of the trees and shrubs have been removed between the fields and on steep slopes during the 19th and 20th centuries to increase agricultural production. This has led to an increase in runoff and soil erosion. Investment in agriculture took off in the 1950's, but was oriented towards export crops such as coffee (Kebbede & Jacob, 1988). Famine because of the succession of dry years between the late 1970s and late 1980s emphasized the needs for land conservation techniques. Directed by the government and with assistance of international programs, soil and water conservation (SWC) activities are currently the most widespread form of agricultural intensification in the Ethiopian Highlands (Haregeweyn *et al*., 2012a; Nyssen *et al*., 2004).

Fieldwork was conducted around Wanzaye in the Lake Tana basin during the rainy season (July-September) of 2013 (Figure 6). Lake Tana is the largest lake in Ethiopia with a total population in its basin of about 3 million inhabitants. The total catchment of Lake Tana covers some 16,500 km², including the lake area. The lake is situated in the northwestern part of Ethiopia (between 11°00'N and 12°50'N, 36°30'E and 38°20'E), forming a depression in the Ethiopian Highlands at 1786 m a.s.l. (Setegn *et al.*, 2010) (Figure 6). Approximately 40 rivers are draining into the lake. More than 90% of the runoff is contributed by four catchments: Megech, Rib, Gumara and Gilgel Abbay (Kebede *et al.*, 2006). The city of Bahir Dar, which is located on the southern shore of Lake Tana, is the fastest growing and the third largest city in the country (Haregeweyn *et al.*, 2012b). Lake Tana is the source of the Blue Nile River.

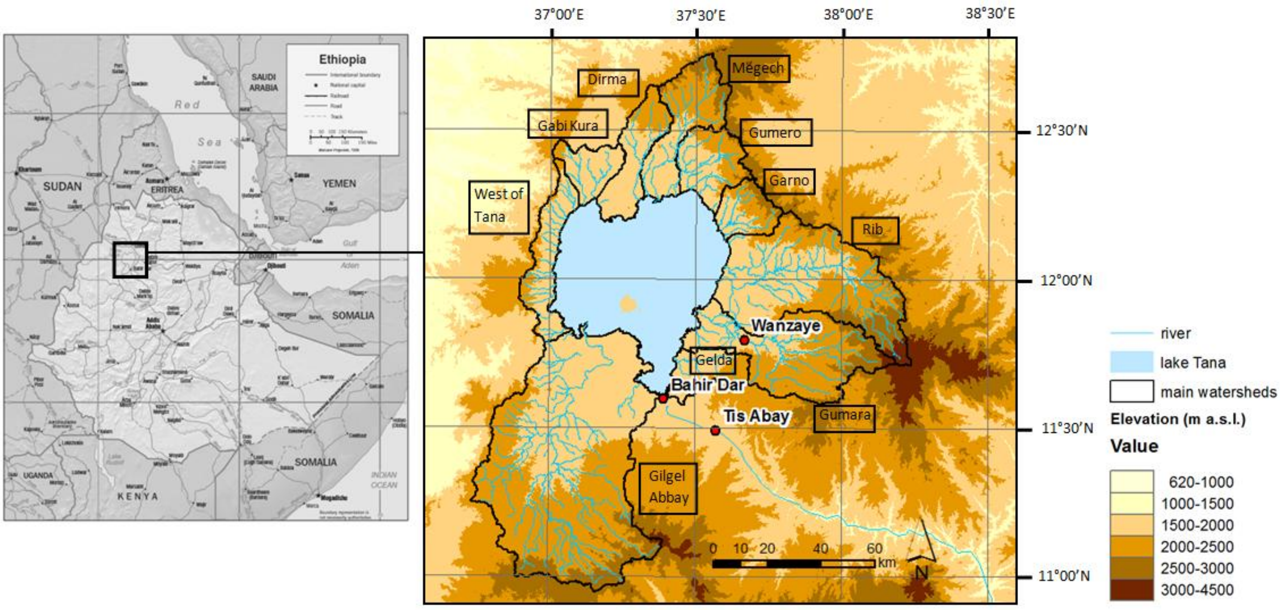


Figure 6. Situation of the study area in the Gumara catchment, which is one of the 10 catchments of the Lake Tana basin.

The climate in Lake Tana basin is "cool to cold tropical highland monsoon" (Dargahi & Setegn, 2011). The average temperature in the catchment is 18 °C ± 4 °C with large diurnal variation of ± 15 °C (Dargahi & Setegn, 2011). Rainfall in the Lake Tana basin is highly seasonal with more than 70% of the rainfall occurring in the *Kiremt* season (June-September). Rainfall is locally variable in the region, with a basin-wide annual average of 1421 mm (Conway, 2000). The major soil types of Lake Tana basin are Nitisols, Vertisols, Luvisols, Regosols and Phaeozems with a dominant presence of the Vertisols and Nitisols (Colot, 2012). The soils of the Lake Tana basin are derived from weathered volcanic rocks. Quaternary volcanoes and Tertiary volcanic plugs are visible in the landscape (Engida, 2010; Poppe *et al.*, 2013). The most important parent materials are mafic rocks and lacustrine deposits (Colot, 2012). The majority of the basin has deep to very deep soils whereas soils on hill slopes are shallow or very stony (Easton *et al.*, 2010; Kebede *et al.*, 2011; Engida, 2010).

The major cereals cultivated in the region are *Eragrostis teff* (tef), *Eleusine coracana* (finger millet), *Oryza sativa* (rice), *Triticum aestivum* (wheat), *Zea mays* (maize), *Hordeum vulgare* (barley) and *Linum usitatissimum* (flax, locally known as telba). Common pulses and oil crops are *Guizotia abyssinica* (niger seed or *neug*), *Brassica carinata* (Ethiopian mustard), *Lens culinaris* (lentils), *Cicer arietinum* (chick pea or *chimbra*), *Vicia faba* (faba bean), *Lathyrus sativus* (grass pea), *Pisum sativum* (field pea) and *Lupinus spp.* (lupin or *gibto)* (http://213.55.92.108/countrystat, 24 March 2013).

The Lake Tana basin is an important region for Ethiopia in many aspects. Lake Tana is a natural, fresh and permanent water body which reflects its importance in fisheries, hydroelectric production (Tis Abay, Figure 6) and touristic functions. Also the basin's biodiversity is striking whilst the presence of many endemic plant species, endemic birds and large areas of wetland (Poppe *et al*., 2013; Setegn *et al*., 2009, 2010; Colot, 2012). The Lake Tana basin contains lacustrine deposits and the weathering materials of the basalts which enhances fertile soils (Colot, 2012).

2.1.2 Land management practices on farmland around Wanzaye

In Ethiopia, agriculture is the most important economic sector accounting for 81% of the employment (Aquastat, 2005). This makes soil and water as the most critical resources (Easton *et al*., 2010). More than half of the Lake Tana basin is used for agriculture (Setegn *et al*., 2009), whilst the main land use is cropland. Pasture and forests (exclosures, eucalyptus plantations or church forests) account for 15% -19% of the land use in the basin (Tana-Beles WME reports, 2011). The most applied production systems in the Lake Tana basin is the grain-plough complex (Nyssen, personal correspondence, 6 May 2013), whilst the crop production in the Lake Tana basin consists for 70% of cereals which is typical for this system (Westphal, 1975). The biggest challenges of this production system are population growth and a decline of soil fertility (Aquastat, 2005). Soil tillage in the Ethiopian Highlands is mostly done by the use of the *marasha*. This tool is pulled by a pair of oxen to break the ground, providing a weed-free seedbed and enhances infiltration (Temesgen *et al*., 2008). Repeated tillage is required due to the incomplete, V-shaped plowing. A poor soil structure, crust formation and plough pans are undesirable outcomes (Biazin *et al*., 2011). Conventional tillage in the Ethiopian Highlands includes for most of the crops a minimum of three tillage operations (Araya *et al*., 2011, 2012): twice before sowing (before the onset of rain, and after first rain shower) followed by one superficial tillage operation after the seeds were broadcasted (Gebreegziabher *et al*., 2009).

The land management practices in the study area are strongly related to the highly seasonal rainfall pattern. We will consider the three main land management practices applied in Wanzaye as well as in the wider region: (1) stone bunds, (2) drainage ditches (*feses*), and (3) the combined use of stone bunds and *feses* (Monsieurs *et al.*, 2014).

Stone bunds are implemented in specific areas in Lake Tana basin according to the decision of the Ministry of Agriculture. The altitude of the area is one of the decision criteria as the policy reads that erosion control has to start from above, taking gradually the lower areas also into account. Some farmers said that bribery can also affect the location of the stone bund construction. Farmers are not always happy with this decision criteria as they know better the local areas vulnerable to erosion, which are not only those at high altitude but where other factors as slope, slope aspect and land use are decisive (Wei *et al.*, 2007). The construction of stone bunds is a time-consuming and a though labor task for which the government intervenes by making the policy so that all farmers from the neighboring villages are forced to help constructing stone bunds in the designated village or pay a fine. This implies that farmers are not able to construct stone bunds in the areas they know to be vulnerable to erosion, due to time constraints. Nevertheless, farmers agreed that the construction of stone bunds is the best way to prevent soil erosion on sloping farmland.

Drainage ditches (*feses*) are established during the rainy season on sloping farmland for different reasons according to the farmers, which will be elaborated further on. The construction variables of *feses* (top width, depth, gradient and drainage density) depend on the farmer's decision regarding their planted crop, indigenous knowledge and the dimensions of the *maresha* ard plough (Gebreegziabher *et al*., 2009). Drainage ditches are perceived as the best conservation practice if no stone bunds are present. *Feses* draining the excess of water into a neighboring farmer's field may cause tension between upslope and downslope stakeholders as this excess of water is an extra source of erosion towards the downslope area (Smit & Tefera, 2011). Although the combined use of stone bunds and *feses* is formally forbidden by the regional Ministry of Agriculture (as stone bunds can be destroyed by drainage ditches), a common practice in the study area is the implementation of stone bunds as well as *feses* on cropland. The malfunctioning of stone bunds or an excess of water that needs to be drained away are reasons mentioned by the farmers for the use of a mixed land management.

In the Lake Tana basin, positive effects for surface runoff and soil loss have been found by the use of stone bunds (Schürz *et al*., 2013; Brenner *et al*, 2013). Other research confirms the positive off-site and on-site effects of stone bunds (Haregeweyn, 2005). But over a longer time span, possible negative consequences such as concentration of runoff, accumulation of water, tunneling under the structures or fertility gradients have to be taken into account (Nyssen *et al*., 2007; Alt *et al*., 2009). On-site-conservation methods on farmland are still in an experimental stage and not widely practiced (Nyssen & Dessie, personal correspondence, 9 April 2013). An absence of local-level organs for guiding irrigation operation has resulted in very few irrigation practices in the Blue Nile catchment, whilst there is potential for irrigation schemes in the region (Colot, 2012; Awulachew *et al*., 2008; Aquastat, 2005). As this research will be conducted on inclined land, this study will however not further investigate irrigation.

2.1.3 Kizin and Wonzima catchments

Fieldwork was conducted in the Kizin and Wonzima catchments during the rainy season (July-September) of 2013 (Figure 7). For two and a half months, a small house was rented in the village of Wanzaye, where the hot spring was a source of water and sanitation. The study areas were reached on foot accompanied by a local translator, Solomon Mulatie, who was a university student living in Wanzaye with his family during the summer break. Soil samples were transported for ten kilometers by a donkey from Wanzaye to the main road, whereafter the WASE-TANA project car could pick up the samples to transport them to the soil laboratory of the Bahir Dar University. Secondary school students or farmers living in the neighbourhood of the study area, who could read and write, have been searched to work as data collectors, paid by the WASE-TANA project. Two data collectors have been trained to read the rainfall depth from the raingauges in Gedam and Tashmender and ten datacollectors have been trained to measure the runoff depth at the outlet of each subcatchment (Figure 7).

Both the Kizin and Wonzima catchment are moderately to dominantly cultivated. They are part of the Gumara subbasin (1279 km²). Soils in the Gumara subbasin are Eutric Vertisols, Eutric Fluvisols, Chromic Luvisols, Haplic Luvisols and a minority of Eutric Leptosols. The Haplic Luvisols are dominant (Poppe *et al*., 2013). Vertisols can swell or shrink depending on the moisture condition. This is due to the type of clays in this soil, i.e. smectite for the Lake Tana basin (Colot, 2010). Vertisols have a good water holding capacity. Fluvisols are common soils along rivers and lakes. Coarsely textured Fluvisols can be found near the river, while finer textures are found farther from the river. Luvisols are common in flat or gently sloping land. Leptosols are mostly presented in strongly eroding areas (Driessen *et al*., 2001).

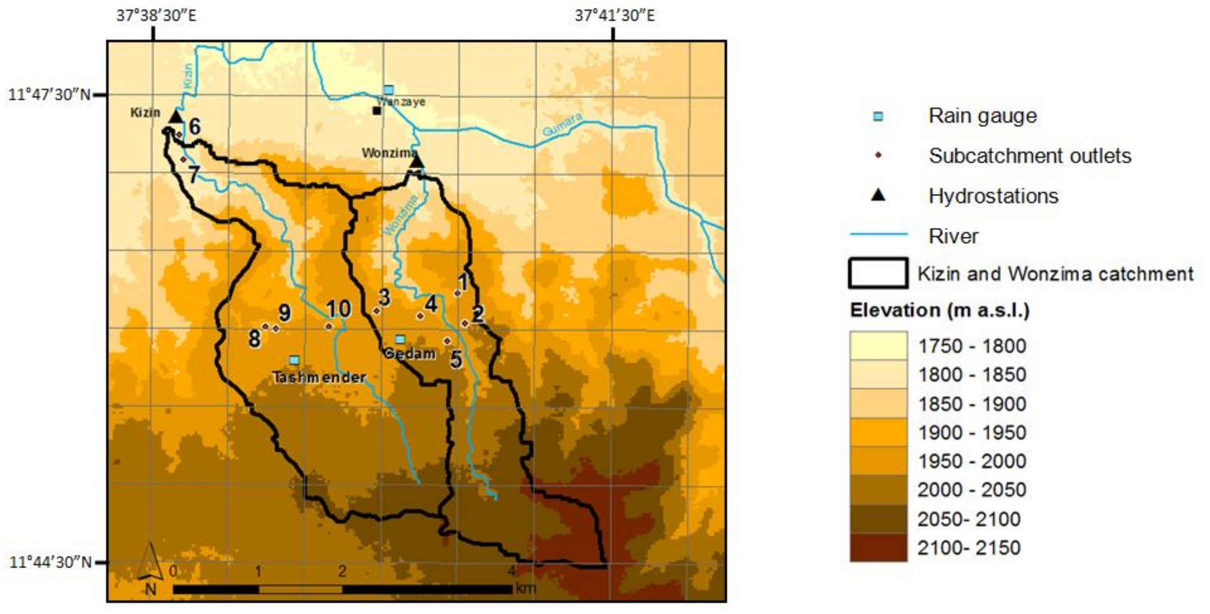


Figure 7. Subcatchments in the Kizin and Wonzima catchments: location of the rain gauges and the WASE-TANA hydrostations. Source: Own editing of ASTER DEM.

The Gumara river is of the braided type and it flows in weathered Tertiary rock. Its sediment transport is low during the dry season but high during the rainy season. The Gumara river erodes its own banks because of this sediment intake and discharge (Poppe, 2012). Poppe (2012) has found river terraces of the Gumara river due to older courses of the river and a higher lake level. The floodplain downstream of the Gumara river is part of the flood risk areas in the Lake Tana basin (Colot, 2012; Engida, 2010).

Google Earth images show clearly the presence of both stone bunds as well as drainage ditches (Figure 8). As the WASE-TANA project is already running since 2010, hydrostations are scattered in the Lake Tana basin. In the hydrostations called "Kizin" (11°47'19.248"N; 37°38'43.019"E)[2] and "Wonzima" (11°46'59.491"N; 37°40'15.755"E)[2] runoff and sediment transport from the study area are monitored in high detail (Figure 7).

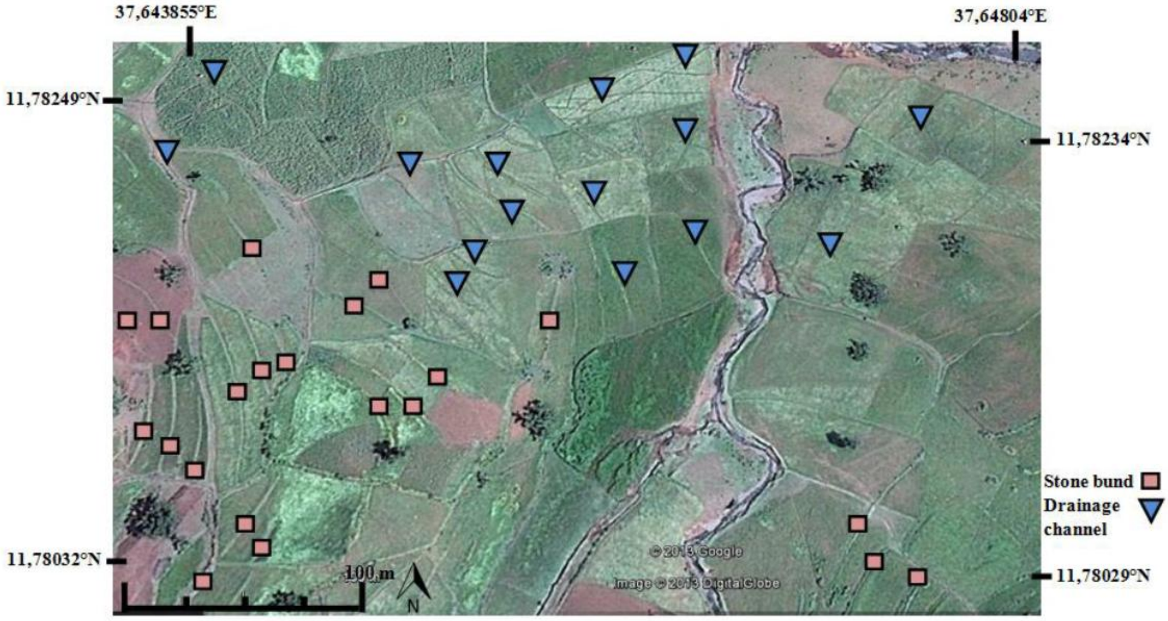


Figure 8. Google Earth image showing drainage ditches and stone bunds. Source: Own editing of Google Earth image.

2.1.4 Subcatchments in the Kizin and Wonzima catchments and land management

After a first survey of the Kizin and Wonzima catchment on Google Earth (Figure 8), fieldwork was conducted to delineate ten study areas by a handheld GPS (Garmin eTrex handheld GPS, vertical accuracy of 3 m). With the aim of analyzing the hydrogeomorphic effects of different land surface management, catchments were chosen with different treatments:

[2] Spatial reference system: WGS84 UTM zone 37N

-Fields without drainage ditches

-Fields including drainage ditches

-Fields with soil or stone bunds

Runoff studies are commonly on plot scale. The major weakness of plot-scale studies is the restriction to extrapolate results from runoff plots towards catchment scale (Nyssen *et al.*, 2004; Awulachew *et al.*, 2008; Nyssen *et al.*, 2010), for which we opted in this research to work on a subcatchments-scale (Figure 7).

The ten study areas are presented in detail in Annex 1. Stone bund and *feses* densities vary for these subcatchments as shown in Table 2. We found one subcatchment without drainage ditches (catchment 2) and two subcatchments without stone bunds (6 and 10). Further on, we will elaborate on the subcatchments' characteristics and the other symbols on the maps in Annex 1.

Table 2. Subcatchments selected for this study and its characteristics: area (ha), average slope (°), average slope gradient (m/m), total *feses* length (m), *feses* density (m/ha), total stone bund length (m), stone bund density (m/ha.

catchment	area (ha)	average slope (°)	average slope gradient (m/m)	total *feses* length (m)	*feses* density (m/ha)	total stone bund length (m)	stone bund density (m/ha)
1	1.9353	11.1	0.20	404	209	1021	528
2	1.7617	3.5	0.06	0	0	789	448
3	4.2109	4.4	0.08	1038	247	306	73
4	3.5106	5.4	0.09	187	53	1364	388
5	1.6348	3.5	0.06	683	418	454	278
6	1.4374	3.2	0.06	584	406	0	0
7	0.7273	3.9	0.07	57	78	276	379
8	0.4105	6.3	0.11	177	431	20	50
9	0.5645	3.5	0.06	106	188	353	626
10	0.2651	13.1	0.23	135	510	0	0
min	0.2651	3.2	0.06	0	0	0	0
max	4.2109	13.1	0.23	1038	510	1364	626
mean	1.6458	5.8	0.10	337	254	458	277
STDEV	1.2507	3.3	0.06	335	179	462	232

2.2 Measuring the biophysical characteristics of the ten subcatchments

2.2.1 Surface conditions during fieldwork

Catchment delineation. Catchment boundaries have been delineated during the setup of the research by detailed field observations with the use of a handheld GPS. The first delineation point was taken at the outlet, whereafter we walked upslope along the catchment boundary, taking GPS points at an interval of approximately 5 m. At each point we evaluated which direction the water would flow during a runoff event. Sometimes flow patterns of a previous runoff event were marked on the field which was very helpful for the catchment delineation. The advantage of this methodology over catchment delineation by GIS software (Poff *et al.*, 2005) is that the actual local field conditions can be captured, for which the importance is stressed by Torri & Poesen (2014). These GPS points and the catchment boundaries have been digitalized in GIS software (Arcmap 10.1) to calculate the drainage area and the catchment-averaged slope (°). The latter was calculated by an automated procedure based on a digital elevation model (DEM) (resolution: 30x30m) in Arcmap 10.1, and converted to slope gradient (m/m) by taking the tangent of each value.

Drainage system/ stone bund system. The location and density of the total artificial drainage system has been monitored by GPS. For each *feses*, a GPS point has been taken at the ends and along the *feses* at an interval of 5 metres. This time-consuming procedure was not necessary for stone bunds as their location is not varying through the years. Stone bunds were easily recognized on Google Earth satellite images, for which their location were checked with photos taken on site. All GPS points have been digitalized in GIS software (Arcmap 10.1) to calculate the length for each segment. Densities are calculated by dividing the total length of *feses* or stone bunds by the total area of the surveyed fields. For calculating the *feses* density per crop, *feses* on the border of two fields were attributed to the upslope field. *Feses* densities did not change during the period of fieldwork (July 15 – September 5). There are some exceptions as for catchment 1 and 5, in which delayed *feses* establishment was caused by the late bed preparation for the postponed sowing of tef. On July 22, 19.4 m of *feses* was constructed in catchment 1 and on August 12, one *feses* with a length of 28 m was constructed in catchment 5. The total *feses* length, including the last constructed *feses* was used for the calculation of the *feses* density for catchment 1 and 5, as we considered these changes in *feses* density negligible.

The angle (°) between the established *feses* and the contour was measured in the field with a protractor (β). These values have been converted to *feses* gradients (m/m) by a formula derived from Figure 9, based on the angle between the *feses* and the contour (β) and the local slope of the surface where the *feses* was located (α):

-In ABCD:

$$a = \sin\beta * L_1 \quad (1)$$

-In ADE:

$$h = \sin\alpha * a \quad (2)$$

-In ACE:

$$h = \sin\gamma * L1 \quad (3)$$

- *feses* gradient (°):

$$\gamma = \arcsin(\sin\alpha * \sin\beta) \quad (4)$$

where α has been derived from a DEM (resolution: 30x30m) in GIS software (Arcmap 10.1), at the pixel where the *feses* was located. The *feses* gradient (m/m) has been calculated by taking the tangent of each γ-value.

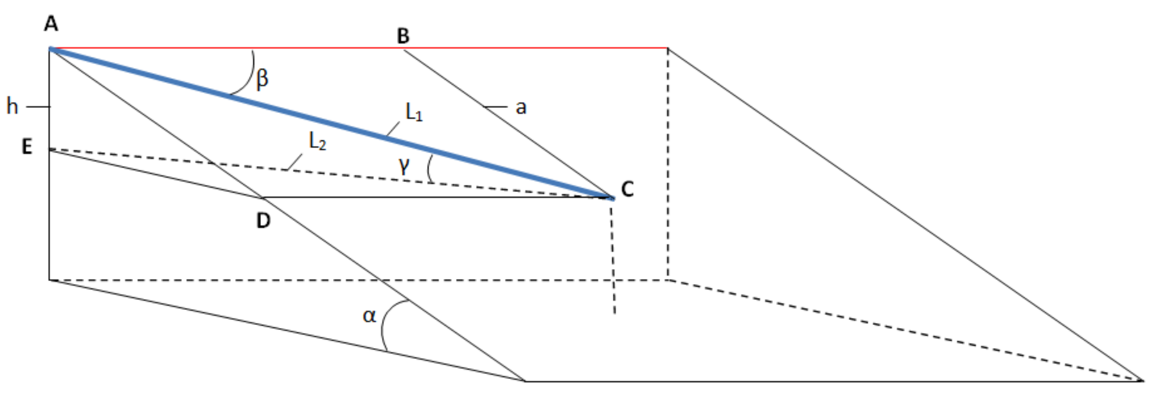


Figure 9. Calculation of *feses* (blue line) gradient, established with an angle β to the contour (red line) on a sloping surface (α).

Evolution of drainage ditches. Depending on the catchment area and the drainage density, monitor sticks have been placed along drainage ditches in order to monitor the *feses*' dimensions (top width and depth) by a ruler. *Feses*' top width and depth has been recorded at the monitoring sticks (Annex 1) right after establishment. During the fieldwork we encountered problems regarding the monitoring sticks placed along the *feses*. Although each data collector was assigned to supervise the monitor sticks placed in his catchment, the sticks got lost by playing children, animals or a heavy rainstorm. Nevertheless, the sticks have been replaced at approximately the same place it was originally put. The area in which the monitor sticks have been replaced will further be referred to as 'monitor sites'. The consequence is that we are limited to qualitative analyses of *feses*' top width and depth, focussing more on the process and intentions of the farmers.

Stoniness. Different methods are used to determine the stoniness of a soil (Poesen & Lavee, 1994). We used the point-count method after Nyssen *et al.* (2006), determining the rock fragment covering the soil surface rather than the rock fragment content of the soil by volume or mass. This methodology consists of systematic observations (n=100) on a straight line (Figure 10.1). Rock fragment cover was calculated as (Nyssen *et al.*, 2001):

$$RFC(\%) = 100\ n_p/n_t \qquad (5)$$

Where RFC is the rock fragment cover, n_p is the number of observations with a rock fragment present (minimum section 1 cm), and n_t is the total number of observations.

Figure 10. Field measurements in Wanzaye (Ethiopia, 2013): (1) measuring stoniness systematically along a straight line in cropland, (2) soil depth measurement, (3) discharge measurements using the float method.

2.2.2 Soil characteristics during the fieldwork period

Moisture conditions and bulk density. To characterize the moisture conditions and bulk density through time, three sample campaigns were conducted during summer 2013: on July 19, August 12 and September 5. During these campaigns, one sample was taken for each catchment in the upper part of the catchment area and one for the lower part, indicated on the maps (Annex 1). Samples are coded in the following way: [CA] catchment, [number] number of the catchment, [L or B] refers to the sample taken in respectively the lower part or upper part of the catchment. In total we collected for each sample campaign 20 undisturbed samples. These samples were taken with Kopecky core rings (Figure 11).

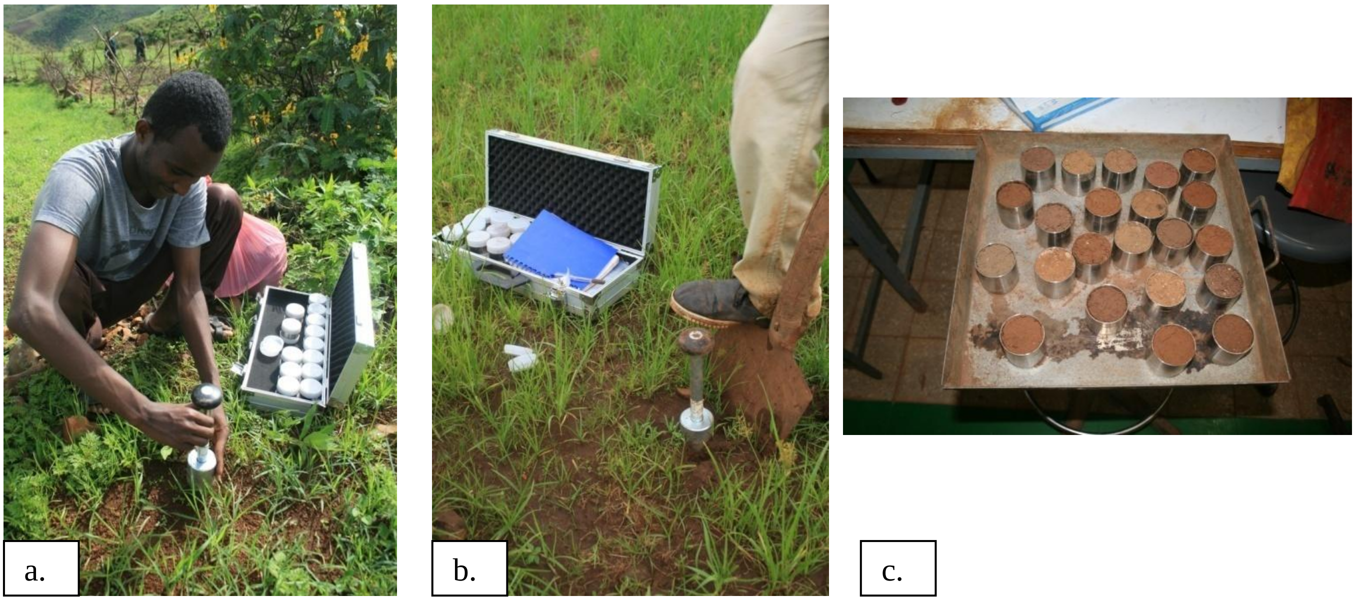


Figure 11. Soil sampling with Kopecky core rings (Wanzaye, Ethiopia, August 2013) (a,b) and soil samples after oven-drying in the soil laboratory of the Bahir Dar University (Bahir Dar, Ethiopia, August 2013) (c).

Soil samples were taken to the soil laboratory of the Bahir Dar University, where the samples have been weighted on a balance before oven-drying to obtain the wet sample mass (M_w). Then, the samples were oven-dried for 24 hours at 105°C and the dry sample mass were weighted (M_s). Bulk density (ρ_b) was calculated by dividing the mass of dry soil (M_s) by its volume (V) (Hillel, 2004):

$$\rho_b = M_s / V \qquad (6)$$

The volume of the soil sample is known because of the calibrated Kopecky core rings (100 cm^3). Gravimetric soil moisture content (Θ, m^3/m^3) has been calculated on oven dry weight basis (Gardner, 1986):

$$\Theta = (M_w - M_s) / M_s \qquad (7)$$

To check if the gravimetric soil moisture conditions change over time, we tested if these values were statistically different from each other. A Repeated Measures ANOVA test was performed in SPSS, which is applicable in this case as we will compare related, non-independent data. The Repeated Measures ANOVA test is based on three assumptions, which are verified by the use of a statistical programme (SPSS): (1) equal variance between the successive groups, (2) normally distributed data, and (3) equal covariance between the successive groups.

Our zero hypothesis for the Repeated Measures ANOVA test is that there is no significant difference (significance level $\alpha = 0.05$) in mean gravimetric moisture content for the three data groups (three time records), whereas the alternative hypothesis states that at least one group is significantly different:

$$H_0: \mu_1 = \mu_2 = \mu_3 \qquad (8.1)$$

$$H_A: \mu_1 \neq \mu_2 \neq \mu_3 \qquad (8.2)$$

The Repeated Measures ANOVA test is based on the following equations (https://statistics.laerd.com, 8 April, 2014):

$$SS_{time} = SS_b = \sum_{i=1}^{k} n_i(\bar{x}_i - \bar{x})^2 \qquad (9.1)$$

$$SS_{time} = SS_b = \sum_{i=1}^{k} n_i(\bar{x}_i - \bar{x})^2 \qquad (9.2)$$

$$SS_w = \sum_{1}(x_{i1} - \bar{x}_1)^2 + \sum_{2}(x_{i2} - \bar{x}_2)^2 + \cdots + \sum_{k}(x_{ik} - \bar{x}_k)^2 \qquad (9.3)$$

$$SS_{subjects} = k \cdot \sum(\bar{x}_i - \bar{x})^2 \qquad (9.4)$$

$$SS_w = SS_{subjects} + SS_{error} \qquad (9.5)$$

$$SS_{error} = SS_w - SS_{subjects} \qquad (9.6)$$

$$MS_{time} = \frac{SS_{time}}{(k-1)} \qquad (9.7)$$

$$MS_{error} = \frac{SS_{error}}{(n-1)(k-1)} \qquad (9.8)$$

$$F = \frac{MS_{time}}{MS_{error}} \qquad (9.9)$$

Where,

$SS_b = SS_{time}$ =between-groups variability;

SS_w= within-groups variability;

$SS_{subjects}$= variability due to the individual differences between subjects;

SS_{error} = error variability;

MS_{error} = mean sum of squares for error;

MS_{time} = mean sum of squares for time.

We have 20 subjects (n) and three time records (k).

Silt/clay ratio. Silt/clay ratios have been used in research to assess the erodibility of an area, for which a large silt/clay ratio implies a larger erodibility (Bouyoucos, 1935; Singh & Prakash, 1985; Ben-Hur *et al.*, 1985; Brubaker *et al.*, 1992; Oti, 2004; Wanjogu *et al.*, 2006). For each catchment two disturbed samples were taken at the same places as for the samples for moisture and bulk density analysis (Annex 1). The catchment code is also built up in the same way as for moisture and bulk density analysis. The sand fraction has been discarded from the sample by dry sieving. The fraction smaller than 65 µm has been analyzed by the use of a sedigraph at the laboratory of the Ghent University to distinguish the silt fraction (2-63µm) from the clay fraction (<2µm) (Beuselinck *et al.*, 1998).

Soil depth. Soil depth up to one meter was measured in cropland at four places per catchment or at two places for small catchments (catchment 7 and 10) (Annex 1), which was used to determine the soil depth for each catchment. To limit possible destruction to the farmer's crop, a long iron rod was used to loosen the soil for digging a hole by hand of approximately 25 cm diameter (Figure 10.2).

2.3 Interviews

During the fieldwork in Wanzaye, information was gathered by interviewing landowners in the catchments by the assistance of a trustworthy local translator. Also farmers outside the ten study areas using *feses* were questioned about their land management to confirm the stories told by the farmers in the ten subcatchments. For each different crop in the catchment, the farmer was asked to give the local name. The main questions regarding land management were:

- If only *feses* are present (no stone bunds):

(1) Why do you use *feses* ?

(2) Where do you construct the *feses*? Is it every year at the same place?

(3) When do you construct *feses*?

(4) Does it depend on which crop is growing for the establishment of *feses*?

(5) Do you have to maintain *feses* during the rainy season?

(6) Why are you not using stone bunds?

(7) Do you encounter problems caused by *feses*?

  - If yes:

  (8) Are *feses* deepening over time?

  (9) Are there farmers in this area experiencing conflicts caused by the use of *feses* ?

(10) If there would be stone bunds on your farmland, are *feses* than still required?

- If only stone bunds are present (no *feses*):

(11) Why are you not using *feses*?

(12) Since when are these stone bunds present?

(13) Are they a good management tool?

(14) Is it necessary to construct *feses* in fields where stone bunds are present?

- If *feses* and stone bunds are present

  (See questions (1)-(5), (7)-(9), and (12)

(15) Why are you using both stone bunds and *feses*?

(16) What are the benefits of this combined use?

(17) What are the disadvantages of this combined use?

- General question

(18) Is this cultivated field your own property or is it contracted land? Does it have an impact on the way you manage your cropland?

2.4 Rainfall data

Two rain gauges were installed, one for each catchment (Kizin and Wonzima) in which the ten subcatchments are located (Figure 7). Rain gauges were installed in the villages Tashmender (Kizin) and Gedam (Wonzima) and constructed as a copy of the NMSA[3] rain gauges. They have been enclosed by a fence to protect them from disturbing factors such as animals and a minimum distance of two meters to any kind of constructions was kept (in any case, large trees have been avoided) (Figure 12). Secondary school students living in the neighbourhood have been trained to record every evening (18:00) (daytime precipitation) and every morning (07:00) (nighttime precipitation) the volume of water in the rain gauge using a graded cylinder. Quality control of the data and precision checks aimed at minimizing data errors.

Figure 12. Rain gauges installed in Wanzaye (Ethiopia) after the NMSA rain gauges, with a diameter of 20.5 cm (2013).

Rainfall data from both rain gauges have been attributed to the subcatchments located within the rain gauge's catchment. Rainfall data from the rain gauge at Gedam is assigned to subcatchments 1 to 5, whereas data from Tashmender is assigned to subcatchments 6 to 10. Attention has to be drawn to catchments six and seven, which are located 100 meter lower than the rain gauge.

Rainfall has been recorded starting from July 15 to September 5. Volumes have been converted to millimetres:

[3] *National Meteorological Services Agency*

$$\frac{1\ litre}{m^2} = 1mm \quad (10)$$

The upper surface of the rain gauges (where rainfall enters the rain gauge) in Tashmender and Gedam was 330.1 cm^2 (Figure 12). So to convert the data in millilitres to millimetres, the data is multiplied by a conversion factor equal to 0.03.

2.5 Flow depth, channel geometry and discharge calculation

To calculate the runoff discharge at the outlet, two main measurements were conducted: rating curve measurements and routine flow depth measurements. A rating curve shows the relation between flow depth and discharge:

$$Q = a\ h^b \quad (11)$$

Where Q (m^3/s) is discharge, h (m) is the flow depth and a and b are fitting parameters. The velocity (V) was determined by the float method, consisting of measurements with a floating object while the flow depth is recorded (Figure 10.3). Measurements for floating objects which got obstructed by swirls have been omitted. The area of the flow section (A) has been calculated for each flow depth. With this data, discharge (Q) has been calculated: Q (m^3/s) = A (m^2) * V (m/s), for each specific flow depth. Due to time constraints and the unexpected rainfall events during the day, we managed only to construct rating curves for catchments 1, 3 and 4. An attempt was made by outsourcing the velocity measurements to data collectors, although these rating curves did not reflect the field conditions, i.e. unrealistic runoff values. Nevertheless, the computed cross sectional area, wetted perimeter, and hydraulic radius are maintained for further analyses. For the remaining catchments we have to rely on the Gauckler-Manning formula (Manning, 1891):

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (12)$$

Where:

V is the average velocity (m/s);

n is the Gauckler-Manning coefficient [roughness coefficient (Coon, 1995)];

R is the hydraulic radius (m); and

S is the slope (m/m).

As we know that discharge Q is: Q = V*A, where A is the cross-sectional area of the channel flow, we can rewrite the formula above as:

$$Q = \frac{A}{n} R^{2/3} S^{1/2} \quad (13)$$

Firstly the roughness coefficient n, which incorporates the factors that contribute to the loss of energy in a stream channel, has to be determined. The procedure for estimating the n-value is generally subjective for which the accuracy depends on the applicants' experience (Coon, 1995). Therefore we prefer the method put forth by Cowan's (1956) over Chow's (1959) method for it consists of more determining variables which renders thus a less crude estimation. To decrease the subjectivity, eight scientists (geomorphologists) of the Ghent and Bahir Dar Universities who are familiar with the Manning formula and its parameters have been asked to give their estimation for Cowan's parameters determining n, based on photographs of the outlet channel (Figure 13) and by using the form in Annex 2. We took the mean of the estimates for each parameter to estimate the roughness coefficient n. Cowan's (1956) methodology to determine a roughness coefficient n has been used by many researchers in different parts of the world (Kim *et al.*, 2009; Arcement & Schneider, 1989; Marcus *et al.*, 1992). The effects of different types of irregularity are taken into account to quantify the degree of retardation of flow. The procedure entails, first, the selection of a basic value n_0 according to the materials present in the channel ranging from 0.020 for channels in earth to 0.070 for channels composed of boulders. Followed by the assessment of five primary factors affecting n. A value for n_1 is based on the degree of roughness or irregularity of the channel surface ranging from 0.000 ("Smooth") to 0.020 ("Severe"). Changes in shape and size of the cross section, causing significant turbulence, are presented by n_2 for which values range from 0.000 (changes occurring gradually) to 0.015 (frequent alternating large and small channel sections). Another modifying value n_3 considers the presence of obstructions in the cross sectional area, where its relative effect can range from 0.000 ("Negligible") to 0.060

("Severe"). The effect of vegetation causing turbulence is considered in factor n_4 ranging from 0.000 ("Low") to 0.100 ("Very high"). Finally, a modifying value n_5 for meandering of the channel is estimated for which the values range from 1.000 (meandering ratio[4] = 1.0 to 1.2) to 1.300 (meandering ratio ≥1.5). The net effect of all factors causing retardation of flow (n) is calculated as:

$$n = (n_0+n_1+n_2+n_3+n_4)*n_5 \quad (14)$$

Figure 13. Example of the photographs of the outlet channel for subcatchment 1 on which the collective group evaluation for the parameters defined by Cowan (1956) for Manning's roughness coefficient are based (Wanzaye, Ethiopia, 2013).

The cross sectional area for each flow depth was measured using a 2D drawing program (DraftSight) (Figure 14). Inputs for this digitalized presentation and calculations come from measured dimensions in the field by a ruler. The slope (°) of the outlet channel has been measured by a protractor for each catchment and converted to slope gradient S (m/m) by taking the tangent of each value. These slope measurements took place in the channel at the position where flow depths were recorded. The wetted perimeter has been calculated for each flow depth using DraftSight. The hydraulic radius can then be determined using the formula:

$$R = \frac{A}{P} \quad (15)$$

where R= hydraulic radius (m), A is the cross sectional area of flow (m^2) and P is the wetted perimeter (m). After the roughness coefficient was determined for all catchments, discharges

[4] Meandering ratio = meander length/ straight length (Chow, 1959)

for different flow depths were calculated using equation (13). Subsequently, rating curves in the form of eq. 11 could be constructed for all catchments.

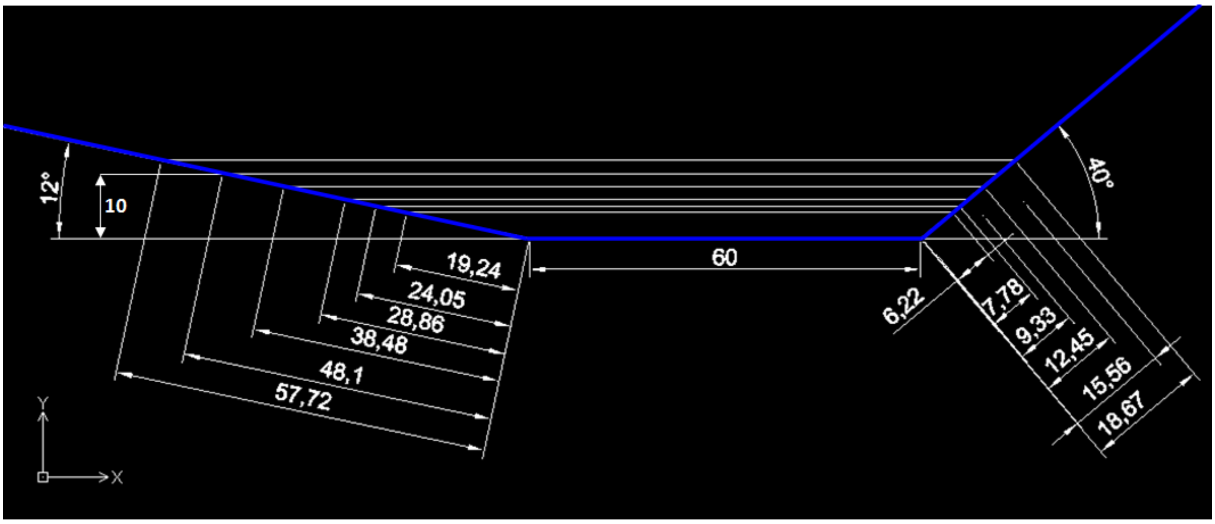


Figure 14. Drawing of the outlet channel of catchment 1 using DraftSight for calculation of the cross-sectional area and and the hydraulic radius. Values are presented in cm.

2.6 Runoff analyses

Secondary school students or farmers who could read and write, living in the neighbourhood of a catchment outlet, have been trained to record for every rainfall event flow depths at the outlet channel at an interval of five minutes. These routine flow depths are converted to continuous runoff discharge series by the calculated rating curves (Nyssen *et al.*, 2010; Descheemaeker *et al.*, 2008; Rodriguez-Blanco *et al.*, 2013).

For each rainfall event, maximum discharge (Q_{max}), total runoff (mm), and runoff coefficient (RC) (%) were calculated. The latter was calculated as a fraction of the measured daytime rainfall (at 18:00), resulting in underestimations of the RC if daytime rainfall comprises rainfall event(s) prior to or after the runoff measurement. RCs could have been calculated more precisely when the time resolution was higher. Q_{max} has been normalized by the catchment area (A) (Q_{max}/A), enabling a comparison between the study areas.

Discharge measurements in function of time (hydrograph) are plotted for the measured runoff events. The shape of the hydrograph (peak/flat) and the lag time are interesting parameters to compare for the different catchment. Yet, the latter will not be discussed as in the beginning of the fieldwork, runoff has not been consequently measured from the very beginning of a runoff event due to the inadequate training of the data collectors. Different measures are used by different authors for expressing the peakedness of a hydrograph of which three will be discussed: (1) the kurtosis, (2) velocity of rise time (VRT, $m^3/(10^{-3}*s*m^3)$) and (3) Q_{max} over base time (QBT, $m^3/s/hour$). The kurtosis is a measure of the peakedness of the hydrograph. A minimum value of the kurtosis is -3, for which the histogram is flat; a graph with a kurtosis of 0 is normal distributed; and a graph with a kurtosis higher than 0 (until infinity) is more sharp than if it was normal distributed. In general, 'a low-kurtosis hydrograph has a broad, low-amplitude peak, is more rounded and has a shorter tail' and 'a high-kurtosis distribution has a sharper peak and longer, fatter tails' which reflects a flashy flow regime (Fryirs & Brierley, 2012). Velocity of the rise time is calculated as:

$$VRT = \frac{\mathrm{Qmax} - \mathrm{Qt}}{\mathrm{P} * \mathrm{A}} \qquad (16)$$

where Q_t is discharge at t minutes before Q_{max}, both normalized by daytime rainfall (P, mm) at the date of the runoff event and catchment area (A, m^2). Q_t is taken for t=10, because data at a time longer than 10 minutes before Q_{max} was not always available as the beginning of each runoff event could not always be captured due the unpredictability of rainfall events. QBT is another measure of hydrograph peakedness calculated as the peak discharge to base time ratio. The base time is the base width (time) of the direct runoff portion of the hydrograph (Gregory & Walling, 1973; Gordon *et al.*, 2004). The kurtosis is preferred above VRT and QBT as a measure of the hydrograph peakedness for the following reasons: (1) VRT is only a measure for peakedness during rise time and does not comprise the data of the falling limb of the hydrograph, (2) VRT is limited by t=10 for Q_t for the data of Wanzaye, (3) base time used for QBT is not accurate for data of Wanzaye as runoff events could not always be totally captured, and (4) kurtosis is widely used as a measure for hydrograph peakedness (Hood *et al.*, 2007; Graf, 2010; Kumar & Chatterjee, 2005; Tardif *et al.*, 2009; Fryirs & Brierley, 2012).

2.7 Rill erosion

According to Zegeye *et al.* (2010), who did research in the Debre Mewi watershed in the Lake Tana basin, the maximum rill development (number and dimensions) is attained in August. Hence, to calculate the total volume of rill erosion, rills have been measured at the end of August (2013). The rill volume was measured from its starting point up to the place where the eroded soil was deposited by measuring the length, width and depth with a ruler. Due to time constraints, depth and width of the rills have only been measured at one place along the rill which seamed representative for the whole rill. A GPS point was taken at the starting point of each rill. Aanalyses are based on the calculated rill volumes as it comprise all dimensions of the rill (length, depth, width), rather than analyzing the rill density (m/ha) which only comprises the rill length (Zegeye *et al.*, 2010). Soil loss by rill erosion (ton/ha) has been calculated by multiplying the catchment-averaged measured bulk density and the total rill volume per ha.

2.8 Topographical threshold conditions for gully head development

2.8.1 A standard physical-based model for topographical threshold analysis

A common way to quantify the land susceptibility to gully erosion is to apply a coupled criteria analysis of topographic factors controlling the gully head position (e.g. Morgan & Mngomezulu, 2003; Nyssen *et al.*, 2002b; Poesen *et al.*, 2003). Torri & Poesen (2014) proposed a standard procedure to quantify topographic threshold values, developed from the largest compiled dataset on threshold parameters so far. Standardisation of this procedure is required to enhance a large data set on threshold values from different studies in various environments, which enables calculating threshold parameters in a robust statistical way.

Topographic thresholds are commonly presented as double logarithmic plots of upslope drainage area (A) and slope gradient at the gully head (s). Patton & Schumm (1975) and Begin & Schumm (1979) were pioneers in modelling gully erosion as a threshold process:

$$s \geq kA^{-b} \qquad (17)$$

$$s = \tan\gamma \qquad (18)$$

where γ is the local slope angle (°) of the soil surface and k is an expression for the effects of land use. The upslope area (A) draining towards the gully head is expressed in ha. Gullies which could have been influenced by the presence of roads cannot be used for topographic threshold analysis (Nyssen *et al.*, 2002b). It is emphasized that the slope gradient (s) should be measured as the local slope gradient of the soil surface near the gully head (Vandaele *et al.*, 1996; Vandekerckhove *et al.*, 1998). Torri & Poesen (2014) set the exponent value b as a constant value because b does not show a trend for different land use classes. There is one exception for sites where landsliding occurs at the gully head for which the exponent decreases. The exponent b has been set at 0.38 and 0.5 by Torri & Poesen (2014), based on values used by Montgomery & Dietrich (1994), Nachtergaele *et al.* (2002) and Knapen & Poesen (2010). These values have been assessed by the use of two flow parameters: (1) the Manning formula and (2) the stream power per unit volume (P) for which 0.38 and 0.5 proved to be good estimates of b. The value 0.38 is preferred to 0.5 as it performs better in predicting threshold conditions.

Threshold relations in the form of equation (17) are not robust for which its weakness lies in the arbitrary procedure of the construction of the threshold line due to a poor number of data comprising the threshold situation (Torri and Poesen, 2014). Torri and Poesen (2014) propose an extension of this model:

$$\sin(\gamma) \geq 0.73ce^{1.3RFC}\,(0.00124S_{0.05}-0.037)A^{-0.38} \qquad (19)$$

The sinus is used here to compile a large dataset comprising also large slope angles (γ>15°), which is conform to the original threshold approach of Begin & Schumm (1979) and Patton & Schumm (1975), based on soil shear resistance. Coefficient c represents other factors and processes (e.g. piping) as a source of variation for k, RFC is rock fragment cover affecting the infiltration rate and runoff velocity (Poesen *et al.*, 1990), and S_λ is the maximum potential losses to runoff (with λ the fraction of S which represents the initial abstraction). S_λ can be determined by the Runoff Curve Number Method (Hawkins *et al.*, 2009). This model requires a detailed description of the local environmental characteristics.

Studies reporting topographic thresholds for gully head development quantify the different threshold values for different land use classes. The most common land use categories investigated are cropland, rangeland, pasture, grassland and forest (Achten *et al*., 2008; Vanwalleghem *et al*., 2005; Vanwalleghem *et al*., 2003). The value of k increases for soils with more protection to erosion by vegetation cover (Torri & Poesen, 2014). No differentiation for different management practices in the category cropland has ever been considered, although land management has an important effect on erosion processes (Casali *et al*., 1999; Ligdi & Morgan, 1995; Nyssen *et al*., 2007; Taye *et al.*, 2013). Therefore, the particular conditions of the area around Wanzaye where three types of land management are used on cropland are investigated to reveal the effect of such land management practices on threshold conditions for gully head development. These three types of land management are: (1) stone bunds, a soil and water conservation practice established along the contour (2) drainage ditches (Figure 15), and (3) the combined use of stone bunds and *feses*, which will further be referred to as 'mixed' (Figure 15) (Monsieurs *et al*., 2014).

The three distinctive land management practices (stone bunds, *feses*, mixed) affect the runoff response and erosion processes on cropland in a different way. It will be analyzed whether the topographical threshold values for gully head development are different for these three different land management practices.

Figure 15. Left: the use of drainage ditches (*feses*) during the rainy season. In the back, farmland without *feses* is present on which rill erosion occurs. Observe the absence of rills and channels in the upper shrubland. Right: mixed land management practice with combined use of stone bunds and *feses* in Wanzaye (Ethiopia) (August 2013).

2.8.2 Data collection in Wonzima and Kizin subcatchments around Wanzaye

Although we are aware of the extended standardized model for topographic thresholds (eq. 19), we opted in this research for the model given by equation 17 for its fast and practical implications but which is not as robust as the extended version. RFC for each delineated catchment correlated to a downslope gully has not been measured, neither is sufficient information available to calculate S_λ and c in the extended version (eq. 19). However the same parameters as in the standardized procedure will be used, which enables us to detect trends by comparing our data with the large compiled dataset of Torri & Poesen (2014).

Catchments with exclusively stone bunds (stone bund catchments) (Figure 16), exclusively drainage ditches (*feses* catchments) (Figure 17) and catchments with both stone bunds and drainage ditches (mixed catchments) (Figure 15), all related to a downslope gully head, were delineated by a handheld GPS in the same way the ten study areas discussed earlier had been delineated. In total we delineated 26 *feses* catchments, 27 stone bund catchments, and 22 mixed catchments (Annex 3) for which a specific GPS point was assigned to its correlated gully head. Catchments intersected by roads have been excluded from the dataset, as well as catchments comprising stone bunds constructed after 2003 (marked red in Annex 3). For the latter, gullies might have been formed under previous land management conditions without stone bunds, for which they would be wrongly categorized as 'stone bund catchments' and are therefore excluded for analyses. This filtering of the dataset has been done by the use of historical Google Earth images (Figure 18), which are available for the study area for the years 2003, 2010 and partly also 2013.

The GPS data has further been analyzed by the use of a GIS program (Arcmap 10.0) to deduce the local slope gradient at the gully head (s, m/m) and the upslope drainage area (A, ha). The local slope (°) was derived from a DEM (resolution: 30x30m), at the pixel where the gully head was located.

Figure 16. Gully formed by runoff from upslope stone bund catchment. The slope on which the gully is formed is much steeper than the slope of the catchment. The gully was not formed under the current land management practice (Ethiopia, August 2013).

Figure 17. Gully formed by runoff from upslope *feses* catchment (Ethiopia, August 2013).

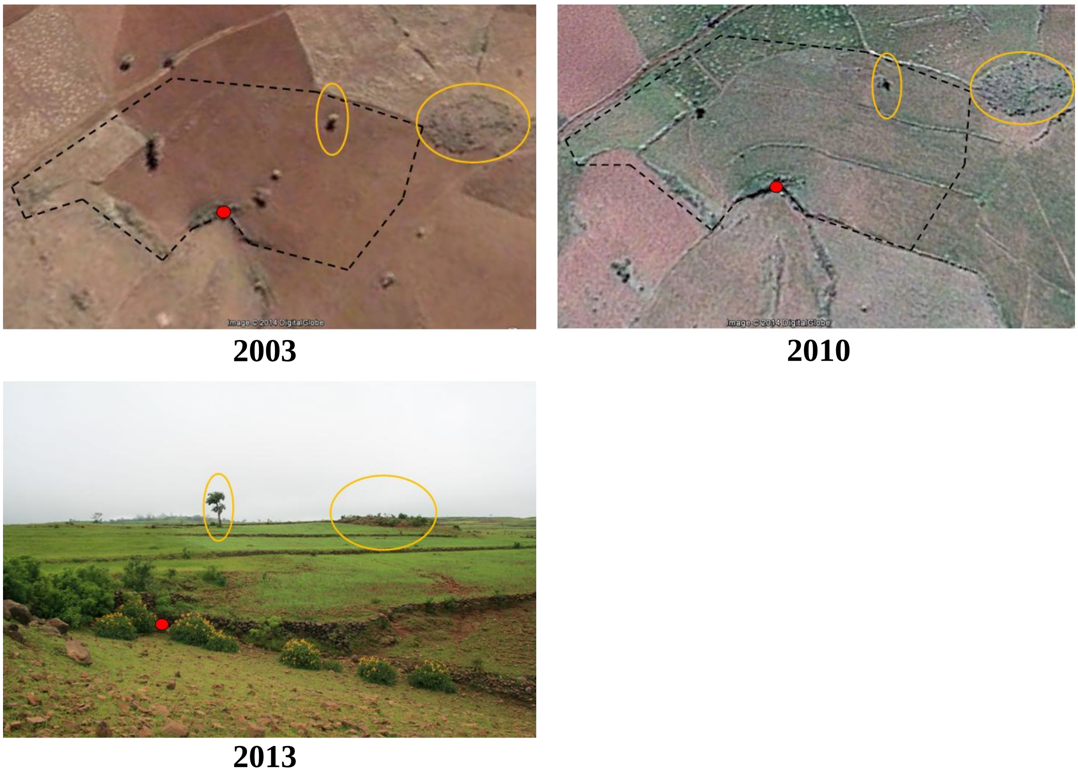


Figure 18. Historical Google Earth image analysis of catchments including stone bunds. Based on the upper left image (2003) the catchment can not be categorized as a stone bund catchment. Whereas we can only see stone bunds appearing in the catchments on the Google Earth image of 2010 (upper right image). The photo below is taken during fieldwork in Wanzaye (2013). The corresponding gully head is marked red and two reference points (tree and bush) are circled.

2.8.3 Setting parameters for a standardized threshold procedure and construction of the threshold line

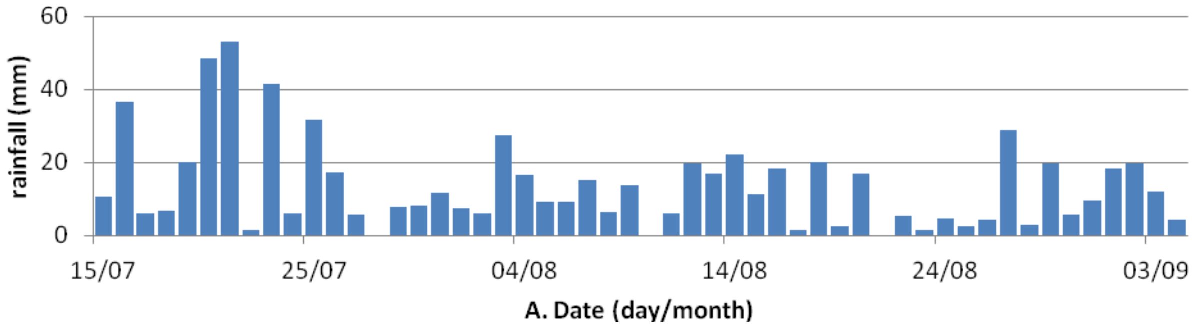
For the exponent b in eq. (17), two values 0.38 and 0.5 are used according to the standardized procedure of Torri and Poesen (2014). To calculate the slope gradient s (m/m) we implement eq. (18) rather than using sinus like in eq. (19) as the former reflects better the concept of ‘slope gradient’ instead of using the abstract shear stress concept on which eq. (17) is originally based upon (Begin & Schumm, 1979; Patton & Schumm, 1975). The mean slope for all catchments is not larger than 18° which is close to 15° for which the tangent can substitute sinus without a significant effect for the topographic threshold (Torri & Poesen, 2014).

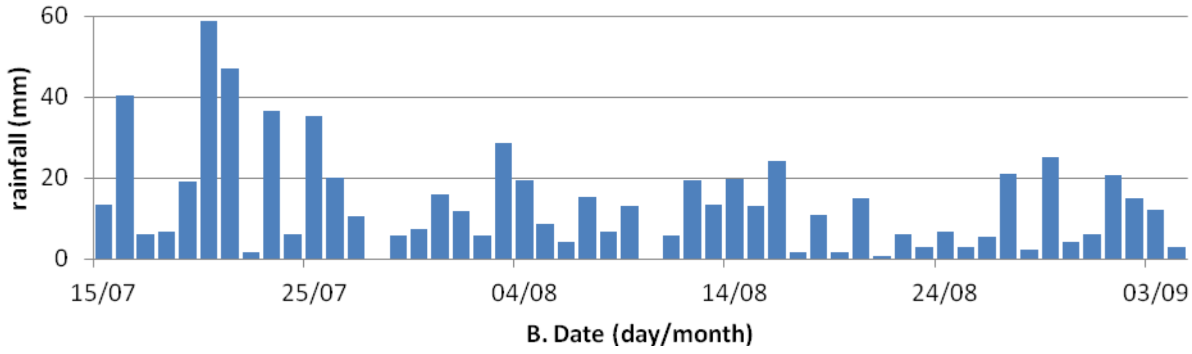
The topographic threshold lines have been defined by first fitting s-A threshold lines for exponents b= 0.38 and b= 0.5 to the dataset, which were then positioned through the lower most data points. This positioning was determined by focusing on the small drainage areas, as these have a higher probability of meeting the assumption that the entire area is contributing to overland flow (Torri & Poesen, 2014).

3. RESULTS

3.1 Rainfall distribution in Wanzaye

Rainfall has been recorded twice a day starting from July 15 to September 5 (Annex 4). Pluviograms for rain gauges in Gedam, Tashmender and Wanzaye (rain gauge of NMSA) are presented in Figure 19 and cumulative rainfall curves in Annex 5.1. The two rain gauges installed in Gedam and Tashmender are highly correlated (Annex 5.2), which is statistically (α = 0.01) tested in SPSS given a correlation value of 0.97 (Annex 5.3). Both installed raingauges are also highly correlated with rainfall measured by the NMSA in Wanzaye (R= 0.85 for Gedam and R= 0.84 for Tashmender, both significant at α = 0.01). Total rainfall depths in Wanzaye, including the data of the NMSA, for the measured period in July, August and September are presented in Table 3. Independent samples t-tests in SPSS showed no significant difference (α = 0.05) of the rainfall depths for rain gauges at Gedam, Tashmender and Wanzaye (NMSA) for July, August and September. Hence, we can assume that rainfall was equally distributed in the whole area. Mean rainfall depth in Wanzaye (during the period of fieldwork) for (15-31) July was 372.35 mm (± 5.78 mm), for August 377.03 mm (± 4.77 mm) and for (1-4) September 66.02 mm (± 5.15 mm).





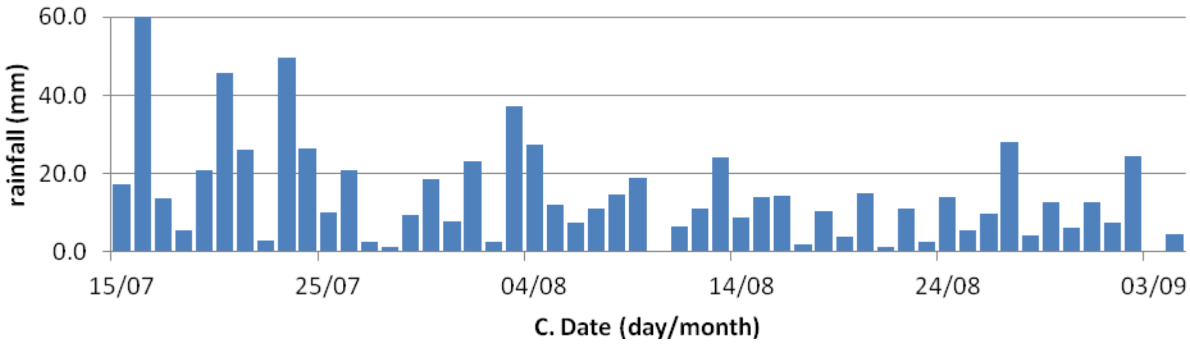


Figure 19. Pluviograms for rain gauges in A. Gedam, B. Tashmender and C. Wanzaye (Ethiopia, 2013).

Table 3. Total rainfall measured in July, August and September (2013) for rain gauges at Gedam, Tashmender and Wanzaye (Wanzaye, Ethiopia, 2013).

	Total rainfall (mm)		
	15 - 31 July	1-31 August	1-4 September
NMSA Wanzaye	371.60	372.90	36.60
Gedam	365.69	383.71	72.21
Tashmender	379.78	374.47	66.26
mean	372.35	377.03	66.02
STDEV	5.78	4.77	5.15

3.2 Biophysical characteristics of the study area during the research period

3.2.1 The use of stone bunds and feses around Wanzaye

The maps of the ten study areas (Annex 1) provide a qualitative overview of the difference in land surface management. Drainage ditches which are not removed after the rainy season by plowing and maintained (at the same place) for use in the next year, are categorized on the maps as ‘permanent drainage ditches’. Whereas drainage ditches which are removed by plowing are categorized as ‘ephemeral drainage ditches’. Although we are aware of the effect of footpaths on runoff (Ziegler *et al.*, 2000; Harden, 1992; Turkelboom *et al.*, 2008), footpaths are not included for further analysis such as the calculation of *feses* density. This choice is grounded by the fact that this study concerns the impact of land surface management on runoff response and footpaths are not considered as a land surface management.

Table 2 and 4 provide a quantitative way of presenting the differences in land surface management over the ten study areas. *Feses* densities range from 0 m/ha to 510 m/ha, with a mean of 254 m/ha (± 179 m/ha). Stone bund densities range from 0 m/ha to 626 m/ha, with a mean of 277 m/ha (± 232 m/ha). The smallest catchment area is 0.27 ha (catchment 10) and the largest is 4.21 ha (catchment 3). The mean catchment area is 1.65 ha (± 1.2507 ha). Catchment-averaged slopes for the ten subcatchments range from 3.2° to 13.1°, with a mean of 5.8° (± 3.3°) and catchment-averaged slope gradients range from 0.06 to 0.23 m/m, with a mean of 0.10 m/m (± 0.06 m/m).

Table 4. Descriptive statistics of the ten subcatchments for their area (ha), slope (°), *feses* density (m/ha) and stone bund density (m/ha).

	area (ha)	slope (°)	slope gradient (m/m)	drainage density (m/ha)	stone bund density (m/ha)
min	0.2651	3.2	0.06	0	0
max	4.2109	13.1	0.23	510	626
mean	1.6458	5.8	0.10	254	277
STDV	1.2507	3.3	0.06	179	232

Stone bunds have been constructed at the initiative of the Ministry of Agriculture in catchment 4 (1975), catchment 1 (1997), and catchment 7 (2012). In catchment 2, stone bunds have been constructed on own initiative in 1982. All farmers in this catchment belong to one family. Also in catchment 3,5,8 and 9 stone bunds are constructed on own initiative.

3.2.2 Crops used in the ten study areas

Crops growing in the study area are: barley, green pepper, onion, maize, millet, potato, telba and tef. The fraction of each crop for the ten catchments is shown in Annex 6. Green pepper and onion are put in the same category as they always occurred together in the study area on beds (Figure 20). Potato was only exceptionally planted by a farmer in catchment 3 for 176 m². This small size of potato cultivation area does not allow observing significant trends, for which this potato field will be omitted from the data. Also green pepper, onion, maize and telba take only a minor place in the catchments as these are more delicate and vulnerable to heavy rains or the seeds are more expensive. Maize is planted close to the homes to protect the plants from animals and theft. On the other hand, millet (locally known as *dagusa*), tef and barley are widely used over the catchments. Only exceptionally, the same crop is sown as the year before, but generally farmers apply crop rotation.

Figure 20. Bed and furrows in Wanzaye (Ethiopia), where green pepper and onion were planted jointly on the beds (July 2013).

3.2.3 Soil depth measured on cropland around Wanzaye

Mean soil depths for all study areas are presented in Annex 7. For small catchments (< 1 ha), two or three field measurements were conducted, whereas for larger catchments the average soil depth was calculated from four or five field measurements. We found average soil depths ranging from 0.17 m to 0.77 m over the ten subcatchments. The mean soil depth for all subcatchments is 0.42 m (± 0.20 m).

3.2.4 Surface stoniness measured on cropland around Wanzaye

The study area around Wanzaye was found to be very stony with an overall surface stoniness of 66.7% (± 26.1%). Systematic observations (n=100) on a straight line have been done approximately 4 times for each catchment. The stoniness ranged from 17% to 99% (Annex 7).

3.2.5 Relation between bulk density and soil moisture

3.2.5.1 Bulk density measured on cropland around Wanzaye

The time- and space-averaged bulk density values from the ten subcatchments are presented in Table 5. The time-averaged bulk density is the average of the three bulk density measurements through time (July 19, August 12 and September 5), for two fixed places per catchment (marked on the maps in Annex 1): one in the upper part of the catchment and one in the lower part. The time specific bulk densities will be discussed further in relation to soil moisture content (Annex 10). The total average bulk density is 1.56 g/cm^3 (± 0.11 g/cm^3). A minimum bulk density was measured in catchment 2 (1.31 g/cm^3), and a maximum in catchment 1 (1.74g/cm^3).

Table 5. Average bulk densities for ten catchments in Wanzaye, Ethiopia. Each value for the 'time-averaged' bulk density is an average of the three sample campaigns (July 19, August 12 and September 5). Sampling was done always at the same place in the catchment: one sample was taken at a fixed place in the upper part of the catchment (B) and one at a fixed place in the lower part (L), both are used for the calculation of the 'time- and space-averaged' bulk density.

catchment code	time-averaged bulk density of topsoil (g/cm³)	time-and space-averaged bulk density of topsoil per catchment (g/cm³)
CA1L	1.46	1.60
CA1B	1.74	
CA2L	1.31	1.44
CA2B	1.58	
CA3L	1.63	1.64
CA3B	1.66	
CA4L	1.56	1.57
CA4B	1.57	
CA5L	1.57	1.63
CA5B	1.69	
CA6L	1.64	1.55
CA6B	1.46	
CA7L	1.68	1.65
CA7B	1.62	
CA8L	1.37	1.45
CA8B	1.53	
CA9L	1.49	1.54
CA9B	1.59	
CA10L	1.46	1.49
CA10B	1.51	
total average bulk density of topsoil (g/cm³)		1.56
STDEV		0.11
min		1.31
max		1.74

3.2.5.2 Gravimetric soil moisture content

Average soil moisture content for the successive sampling campaigns varied over time: 33.4% on July 19, 35.2% on August 12, and 33.3% on September 5 (Annex 8.1). Rainfall prior to the soil sampling is very similar for the Kizin and Wonzima catchments (Annex 8.2). To check if the gravimetric soil moisture conditions changed over time, we tested if these values were statistically different from each other through a Repeated Measures ANOVA test in SPSS.

First, the assumptions to perform this test have been checked. The Levene's test proved equal variances ($\alpha = 0.05$) for the three data groups (July 19, August 12, September 5) (Annex 9.1). QQplots of the data showed normal distribution of the gravimetric soil moisture content, with acceptable deviations (Annex 9.2). Covariances between successive groups (July 19, August 12, September 5) were proven equal ($\alpha = 0.05$) (Annex 9.3), hence all assumptions were met. We found for our dataset the following values:

SStime= 0.004543
SSw= 0.303185
SSsubject= 0.195049
SSerror= 0.108135
MStime= 0.002271
MSerror= 0.002846
F-statistic= F(2,38)= 0.798171

Regarding the F-statistic, we cannot reject the H_0-hypothesis (eq. 8.1, $\alpha = 0.05$), which implies that there is no significant effect of time on gravimetric moisture content. The antecedent moisture conditions of the soil are equal over time.

3.5.2.3 Bulk density and soil moisture content

The mean bulk density over all study areas is 1.53 g/cm³ for July, 1.57 g/cm³ for August, and 1.58 g/cm³ for September (Annex 10). These values are not significantly different (tested in SPSS by an independent samples t-test, $\alpha = 0.05$). Combining this data with the moisture content values (Annex 8.1), allows to analyze the relation between both factors. Similar to the study of Kamara & Haque (1987), a curvilinear relation (quadratic) has been constructed in SPSS, with a coefficient of determination $R^2= 0.001$ (Figure 21).

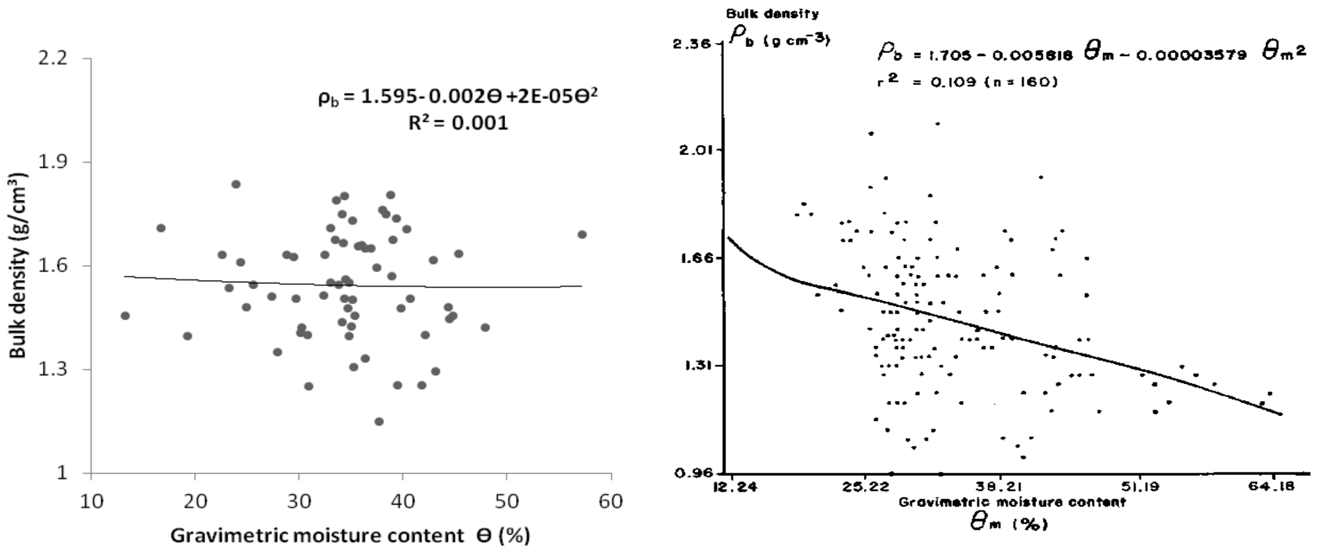


Figure 21. Relationship between gravimetric soil moisture content and bulk density for soil samples taken during the rainy season at Wanzaye (Ethiopia, 2013) (left), and for a Vertisol at Shola, Ethiopia (right) (Kamara & Haque, 1987).

3.2.6 Silt/clay ratio

A mean silt/clay fraction was found of 2.97 (± 1.30) over all study areas (Table 6). A minimum silt/clay fraction was measured in catchment 5 with a ratio of 1.43 and a maximum ratio was found in catchment 7 with a ratio of 5.52. As a larger silt/clay ratio implies a larger erodibility (Benett, 1939; Kuron & Jung, 1957; Wischmeier & Mannering, 1969; Le Bissonnais *et al.*, 1993; Toy *et al.*, 2002), catchment 7 was found to be relatively the most erodible and catchment 5 the least erodible.

Table 6. Silt/clay ratios for soil samples in Wanzaye, Ethiopia.

catchment CODE	silt/clay
CA1L	2.08
CA1B	1.60
CA2L	1.81
CA2B	1.60
CA3L	3.76
CA3B	1.54
CA4L	3.69
CA4B	3.54
CA5L	5.04
CA5B	1.43
CA6L	3.20
CA6B	1.43

CA7L	1.99
CA7B	5.52
CA8L	4.76
CA8B	2.19
CA9L	3.50
CA9B	3.19
CA10L	4.41
CA10B	3.19
mean	2.97
STDEV	1.30

3.3 The use of *feses* around Wanzaye

3.3.1 Observed characteristics of feses

3.3.1.1 Top width and depth right after establishment

Feses are established by a *marasha* ard plough, pulled by a pair of oxen. The catchment-averaged top with of the *feses* measured right after establishment ranges from 0.17 m to 0.44 m. A mean top width of 0.27 m (± 0.09 m) was found. *Feses* are on average constructed with a depth of 0.12 m (± 0.02 m). Catchment-averaged *feses'* depth ranged from 0.08 m to 0.14 m (Annex 11).

3.3.1.2 Evolution of the *feses*' depth during the rainy season

Photos taken at the monitor sites provide material to analyze the *feses'* depth qualitatively. Two evolutions of *feses* through time have been observed: (1) sedimentation of the *feses*, and (2) deepening of the *feses*. This is illustrated for catchment 1 in Figure 22. The *feses* at monitor site 5 in catchment 1 (location of each monitor stick is shown on the maps in Annex 1) shows sedimentation in the beginning of the rainy season (July 25). In August and September, no clear deepening of the *feses* is visible and it seems that small stones inside the *feses* are protecting it. On the other hand, for the *feses* at monitor site 6, degradation of the *feses* is clearly visible. Also for catchment 3 we observed the same two possibilities for *feses* to develop through time (Annex 12). At monitor site 3 in catchment 3, no deepening of the *feses* is visible and weeding material is filling the *feses* in September. At monitor site 4, deepening of the *feses* over time is visible.

Figure 22. Monitor site 5 (upper) and 6 (lower) in catchment 1 for three time records: July 25, August 11, and September 1 (Wanzaye, Ethiopia, 2013). For monitor site 5, no clear deepening of the *feses* is visible, whereas for monitor site 6, degradation of the *feses* is clearly visible.

A classification was made for all monitor sites at the end of the rainy season (on September 1, the monitor sites have last been monitored) differentiating *feses* that got sedimented, *feses* which had been eroded deeper, and *feses* for which the development was not clearly visible (Annex 13), summarized in Table 7. Of all monitor sites, 47% comprised sedimented *feses*, 45% deepened *feses*, and 8% comprised *feses* which showed no clear development.

Table 7. Classification of *feses* at the end of the rainy season (September 1, 2013) for: *feses* which got sedimented, *feses* which had been eroded deeper, and *feses* for which the development was not clearly visible. The number of observations for each classification is presented under 'count' and the fraction of all monitor sites is presented under 'fraction'.

classification *feses*	count	fraction (%)
sedimented	18	47
eroded	17	45
unclear	3	8

3.3.1.3 *Feses* gradient

The measured angles between *feses* and the contour line (β, °), the surface slope at the place where the *feses* is located (α, °), and the calculated *feses* gradients (m/m) (using eq. 4) have been listed in Annex 14.1. *Feses* are found to be constructed at an average angle of 44.7° (± 7.2°) with the contour line. A minimum (catchment average) angle with the contour is 31.1° and a maximum average angle is 56.7° (Annex 14.2). Individual observations of angles between the established *feses* and the contour line range from 0° (parallel to the contour) to 90° (perpendicular to the contour). A mean *feses* gradient measured for all study areas is 0.055 m/m (± 0.054 m/m), ranging from 0.012 m/m to 0.191 m/m.

3.3.1.4 *Feses* density per crop

The total length of the established *feses* varies for the different crops over the study area (Table 8). No *feses* were used for maize. The crop-averaged *feses* density, for crops where *feses* are used, is 203m (± 90m). The highest *feses* density is found for green pepper and onion (372 m/ha), followed by tef (270 m/ha) and millet (236 m/ha). Lowest *feses* densities are found for telba (135 m/ha) and barley (158 m/ha).

Table 8. Total length of *feses* (m) established per type of crop during the rainy season in Wanzaye (Ethiopia, 2013) and the total area (ha) of each crop for the ten study areas, for which the *feses* density is calculated (m/ha). The mean and standard deviation (STDEV) has been calculated without the values of potato and maize.

crop	total area (ha)	total *feses* length (m)	*feses* density (m/ha)	
barley	1.3364	211	158	
green pepper and onion	0.2763	102	372	
maize	0.2065	0	0	
millet	6.6703	1576	236	
telba	0.6576	89	135	
tef	5.1518	1392	270	
			mean	203
			STDEV	90

3.3.1.5 Correlation matrix for land surface management and variables describing the environment

A significant negative correlation (α = 0.05) was found in the ten catchments between stone bund density and *feses* density (R= -0.72) (Table 9). Significant correlations are found between the catchment-averaged slope (°) and the fraction of cultivated barley (R= 0.65), millet (R= -0.66), surface stoniness (R= 0.67) and the catchment-averaged soil depth (R= -0.64). Only crops which were often used over the ten subcatchments (barley, millet, tef) were incorporated in the correlation matrix. Also the following relations have been found significant (α = 0.05): tef and millet (R= -0.64), tef and bulk density (R= 0.64), surface stoniness and soil depth (R= -0.81), top width and depth of the constructed *feses* (R= 0.78), the catchment-averaged silt/clay ratio and depth of the constructed *feses* (R= 0.71), the angle of the constructed *feses* and the contour with stone bund density (R= 0.749), the angle of the constructed *feses* and the contour with *feses* density (R= -0.671), and the angle of the constructed *feses* and the contour with top width of the constructed *feses* (R= 0.684).

Table 9. Output in SPSS for Pearson correlations (PC) between the following variables: stone bund density (SBD), *feses* density (FD), fraction of cultivated barley, millet or tef, surface stoniness (stoniness), soil depth, top width of *feses* (top width), depth of *feses* (depth_f), silt/clay ratio (silt_clay), bulk density (BD), catchment-averaged slope (°) (slope), angle of the constructed *feses* and the contour (°), and *feses* gradient (f_gradient) for the ten subcatchments in Wanzaye (Ethiopia, 2013). Data of all study areas is included (N=10).

Correlations

		SBD	FD	barley	millet	tef	stoniness	soil_depth	top_width	depth_f	silt_clay	BD	slope	angle_contour	f_gradient
SBD	PC	1	-.721*	-.463	-.053	.373	.205	-.049	.325	-.172	-.191	.148	-.170	.749*	.276
	Sig. (2-tailed)		.019	.178	.883	.288	.570	.893	.360	.634	.598	.683	.640	.020	.440
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
FD	PC	-.721*	1	.531	-.246	-.262	.145	-.395	.242	.416	.257	-.128	.374	-.671*	-.039
	Sig. (2-tailed)	.019		.114	.493	.464	.690	.259	.501	.232	.474	.724	.288	.048	.915
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
barley	PC	-.463	.531	1	-.351	-.462	.307	-.291	.064	.113	.344	-.274	.652*	-.174	-.126
	Sig. (2-tailed)	.178	.114		.319	.179	.388	.415	.860	.756	.330	.443	.041	.654	.728
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
millet	PC	-.053	-.246	-.351	1	-.638*	-.256	.316	-.441	-.330	-.447	-.387	-.664*	-.053	-.420
	Sig. (2-tailed)	.883	.493	.319		.047	.475	.374	.202	.352	.195	.269	.036	.892	.227
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
tef	PC	.373	-.262	-.462	-.638*	1	-.169	.083	.232	.148	.176	.635*	.014	.172	.354
	Sig. (2-tailed)	.288	.464	.179	.047		.642	.819	.518	.683	.628	.048	.969	.659	.316
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
stoniness	PC	.205	.145	.307	-.256	-.169	1	-.810**	.179	-.078	.011	-.501	.666*	.032	.343
	Sig. (2-tailed)	.570	.690	.388	.475	.642		.004	.620	.831	.977	.140	.035	.934	.332
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
soil_depth	PC	-.049	-.395	-.291	.316	.083	-.810**	1	-.298	-.053	-.163	.519	-.637*	.097	-.299
	Sig. (2-tailed)	.893	.259	.415	.374	.819	.004		.403	.885	.654	.124	.047	.803	.402

	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
top_width	PC	.325	.242	.064	-.441	.232	.179	-.298	1	.787**	.445	.381	.129	.684*	.345
	Sig. (2-tailed)	.360	.501	.860	.202	.518	.620	.403		.007	.198	.277	.723	.042	.329
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
depth_f	PC	-.172	.416	.113	-.330	.148	-.078	-.053	.787**	1	.713*	.432	-.016	.378	.064
	Sig. (2-tailed)	.634	.232	.756	.352	.683	.831	.885	.007		.021	.213	.966	.316	.861
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
silt_clay	PC	-.191	.257	.344	-.447	.176	.011	-.163	.445	.713*	1	.114	.085	.050	-.347
	Sig. (2-tailed)	.598	.474	.330	.195	.628	.977	.654	.198	.021		.754	.816	.899	.326
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
BD	PC	.148	-.128	-.274	-.387	.635*	-.501	.519	.381	.432	.114	1	-.188	.507	.300
	Sig. (2-tailed)	.683	.724	.443	.269	.048	.140	.124	.277	.213	.754		.602	.164	.399
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
slope	PC	-.170	.374	.652*	-.664*	.014	.666*	-.637*	.129	-.016	.085	-.188	1	-.121	.549
	Sig. (2-tailed)	.640	.288	.041	.036	.969	.035	.047	.723	.966	.816	.602		.757	.100
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
angle_ contour	PC	.749*	-.671*	-.174	-.053	.172	.032	.097	.684*	.378	.050	.507	-.121	1	.303
	Sig. (2-tailed)	.020	.048	.654	.892	.659	.934	.803	.042	.316	.899	.164	.757		.428
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10
f_gradient	PC	.276	-.039	-.126	-.420	.354	.343	-.299	.345	.064	-.347	.300	.549	.303	1
	Sig. (2-tailed)	.440	.915	.728	.227	.316	.332	.402	.329	.861	.326	.399	.100	.428	
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

3.3.1.6 Multiple regression for *feses* density

A multiple regression with *feses* density as dependent variable will give insights in the observed explanatory factors for the use of *feses*. The other variables from the correlation matrix in Table 9 are possible independent variables. A premise for multiple regression is no multicollinearity between the independent variables, for which we have to make a choice between the following variables which have a Pearson correlation coefficient higher than |0.5| (absolute values): (1) barley – catchment-averaged slope (°), (2) millet – catchment-averaged slope (°), (3) millet – tef, (4) catchment-averaged slope (°) – stoniness, (5) catchment-averaged slope (°) – soil depth, (6) stoniness – soil depth, (7) top width – depth *feses*, (8) depth *feses* – silt/clay ratio, (9) bulk density – tef, (10) soil depth – bulk density, (11) bulk density – stoniness, (12) angle contour – stone bund density, (13) angle contour – top width *feses*, (14) angle contour – bulk density, and (15) catchment-averaged slope (°) – *feses* gradient. Top width, depth, gradient and angle with the contour of the established *feses* are not taken into account as they do not meet the requirement of causality. A multiple linear regression model was tested using SPSS for the set of independent variables comprising: stone bund density, the fraction of tef, the silt/clay ratio and the catchment-averaged slope.

No inherent landscape elements could be found to explain the variability of *feses* density, only another land management variable, i.e. the stone bund density, has been accepted into the model by the stepwise procedure (Annex 15.1). During the stepwise procedure, variables are entered into the model one at a time in an order determined by the strength of their correlation with the dependent variable. This implies that other variables besides stone bund density do not explain a significant variability for the *feses* density (Annex 15.2), resulting in a simple linear regression (Annex 15.3):

$$FD = 408.513 - 0.558\ SB \qquad (20)$$

Where FD is *feses* density and SB is stone bund density. The coefficient for SB and the constant value are significant ($\alpha = 0.05$). The coefficient of determination R^2 for this model is equal to 0.52 (Annex 15.4), implying that stone bund density explains 52% of the variability in *feses* density. Also a second model was tested for the set of independent variables comprising: stone bund density, soil depth, barley, millet, and the silt/clay ratio. The second tested model gave the same result as the first, excluding all variables except of the stone bund density (Annex 15.5).

3.3.2 Farmers' perception about the characteristics of feses

What follows is a synthesis of the instructive and fruitful discussions with farmers in and around the ten subcatchments during the rainy season of 2013, based on the interview questions as referred to above. Both contrasting as well as like-minded reactions will be discussed.

Moment of establishment. Feses are established right before, right after or during sowing. In general we can say that farmers carried out the same practice of timing, establishing the *feses* at the moment of sowing. In the beginning of the rainy season, when crops are still in the germinating or first growing stages, farmers are maintaining drainage ditches after a heavy rain storm. Maintaining consists of emptying the *feses* and reconstruction of the *feses*' edges with stones and soil (Figure 23). Sedimentation of the *feses* would hamper the performance of the *feses* and destroyed edges could cause rill erosion. The degree in which this maintenance is performed depends on the farmer's abilities and the site location. The farmer in catchment 10 for example, has to deal with a steep slope and has experienced previous years a lot of soil erosion. A low degree of maintenance would directly have an impact on the rate of erosion on his field. *Feses* in fields with barley will not be maintained as too much barley would be destroyed by crossing the field. The way in which a farmer conserves his *feses* is independent from the fact that he works on contracted land or on his own property as the revenues of the field are also for his interest (most contracts are based on a shared yield) and a good management may lead to an extension of the contract.

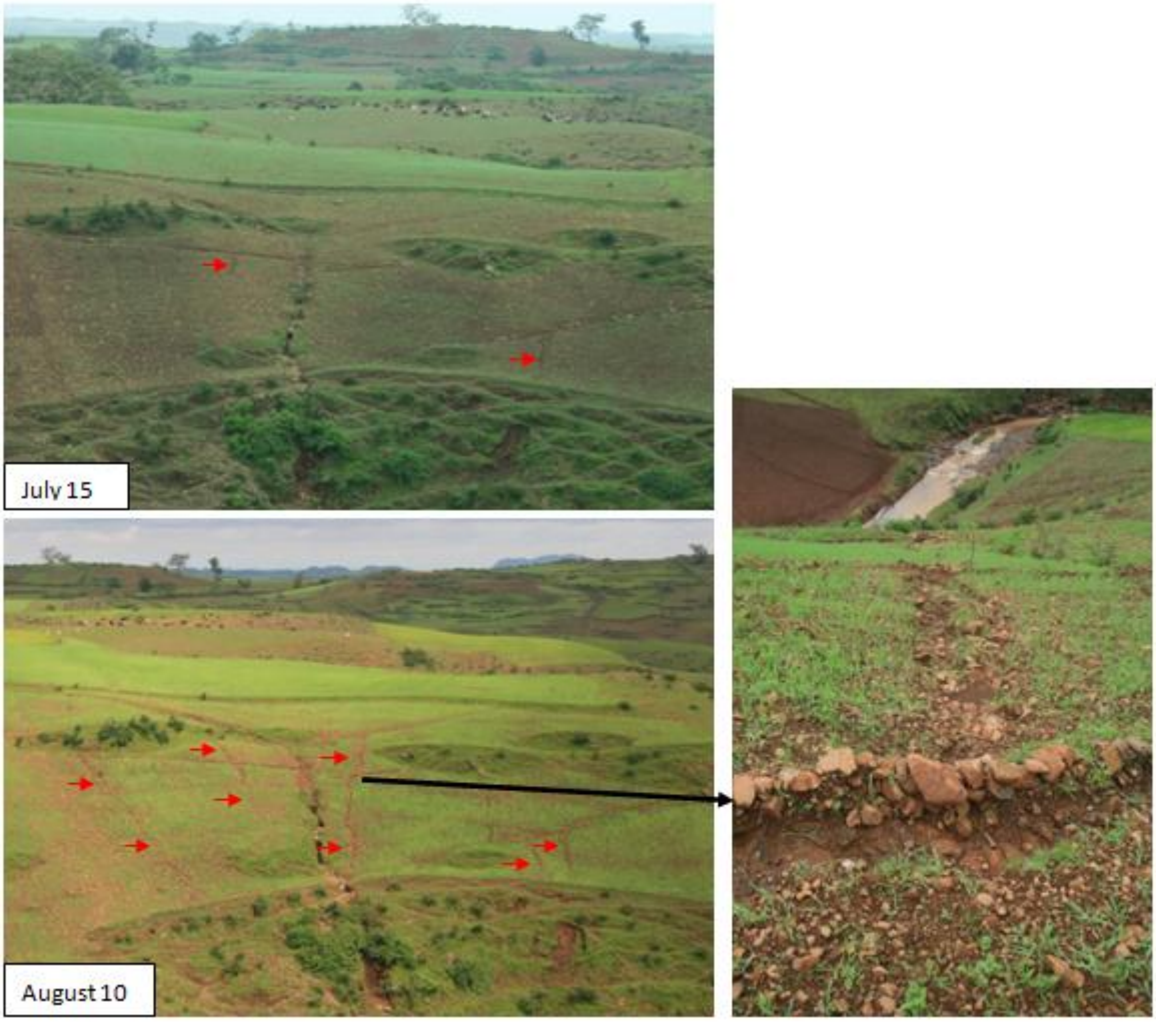


Figure 23. Catchment 10 on July 15 (upper) when only two small rills are present (indicated with a red arrow). On August 10 (lower), several new rills have developed in the area. The farmer has maintained the *feses* by taking out sediment from the *feses* and reconstruction of the *feses*' edge with stones and soil (Wanzaye, Ethiopia, 2013).

Reasons for the construction of feses. Three main reasons are given by the farmers for the establishment of *feses* (Monsieurs *et al.*, 2014): (1) *feses* are required to prevent the loss of seeds right after sowing by overflowing water, (2) on steeper slopes, *feses* are established to avoid erosion by uncontrolled runoff, and (3) *feses* are established on steep as well as flatter areas to drain the accumulated water from upslope areas away. Of the reasons mentioned above, the necessity to drain away accumulating runoff from upslope areas, was the primary motive for the establishment of *feses*, confirmed and repeated by all interviewed farmers.

Constructing feses. Feses are constructed on places where upslope water is accumulating, independent from the crops growing in the field on which the *feses* is made. The fact that *feses* are constructed independent from the growing crops was confirmed by most farmers, although not exclusively. Green pepper for example was mentioned to be very susceptible to erosion by water for which *feses* are required, even when stone bunds are present. It is said that *feses* are not required on grassland as sufficient water will infiltrate. If possible, *feses* are constructed ending in a common pathway. The depth of the *feses* is chosen in such a way that the farmer is able to plow and destroy the *feses* the following year. *Feses* established perpendicular to the topographical contour line are perceived by most farmers as mismanagement of the farmland. Mr. Atalo, who is a local farming specialist, giving information sessions about farming techniques including *feses* construction, explained that such *feses* have no use and will only lead to deep erosion in the *feses* (Annex 16).

Interaction between feses and erosion. Feses are perceived as the best physical conservation technique when stone bunds are lacking. It avoids runoff flowing in an uncontrolled way over the farmers' land. Although, all farmers are aware of its negative implications as well. *Feses* will not be established at the same place as previous year with the reason given by the farmers that the place would be eroded otherwise. Nevertheless, when farmers are asked directly if degradation takes place in the *feses*, answers varied. Either farmers responded positively and confirmed the fact that *feses* are transporting sediments, either farmers responded negatively or were not worried about the magnitude of the degradation. It was said that *feses* parallel to the contour line do not get deeper. It was observed that some *feses* got sedimented indeed. Some farmers said that deepening of the *feses* is not a problem as they are plowed away during the winter. When crops reach a certain height, the roots are strong enough to minimize soil erosion by water and the *feses* loses its function. Farmers will then fill the *feses* by weeding material. It was observed and confirmed by the farmers of catchment 10 that *feses* on steeper slopes are not filled by weeding material, as the *feses*' function remains required and because the power of the water is high that it would remove the weeding material anyway.

Conflicts induced by feses construction. Most of the time, *feses* are establishment in consultation with the owner of the downslope field to drain the water away to a common pathway. If there was no agreement and the downslope farmer encounters erosion problems caused by the upslope *feses*, a community police will intervene. There is only one verdict as the authorities follow the government policy; and hence; the drainage ditch has to be closed. The community police around Wanzaye is very busy during the rainy season solving problems induced by *feses*. Discussions between different farmers and local authorities can take time, although they end mostly peaceful by drinking *tala* (local beer) together.

The use of stone bunds. Stone bunds are seen by the farmers in Wanzaye as the best possible physical conservation measure for their land. Almost all farmers expressed the need for stone bunds on their land but indicated different reasons for which stone bunds are not yet present. Some farmers said it is because of the weakness of the farmer or community. Most farmers explained the absence of stone bunds by a lack of time as they are forced to construct stone bunds in the area designated by the Ministry of Agriculture. During the period of fieldwork, farmers around Wanzaye were obliged to collaborate for stone bund constructions in Debie, a neighboring *kebele* (area comprising different villages) south of Wanzaye. Farmers are collaborating because a fee has to be paid otherwise. Also it is discouraged by the government to construct stone bunds on own initiative as lack of expertise will lead to bad stone bund construction.

All farmers agreed that *feses* are not necessary when stone bunds are present. It would even be detrimental for the power of the concentrated water would destroy the stone bunds. This is why the government forbids the establishment of *feses* (as well as cattle) in an area were stone bunds are constructed by the government. Even though, some farmers do make *feses* in combination with stone bunds, for which different reasons are given by the farmers: (1) no maintenance of the stone bunds and hence malfunctioning, (2) the excess of water needs to be drained away, and (3) water overflowing stone bunds does erode their field (Monsieurs *et al.*, 2014).

3.4 Physical aspects related to different land surface management

3.4.1 Land surface management and its effects on runoff

3.4.1.1 Rating curves catchment 1,3 and 4

Data of the discharge measurements for catchment 1, 3 and 4 are presented in Annex 17, consisting of: depth of flow h (m), area A (m^2) of the cross section, velocity V (m/s) and the measured discharge Q (m^3/s). With this data we are able to construct the rating curves (Figure 24). For catchment 1, coefficient b (equation 11) is much smaller (1.6304) than for catchment 3 (2.7035) and 4 (2.7983) which are more similar.

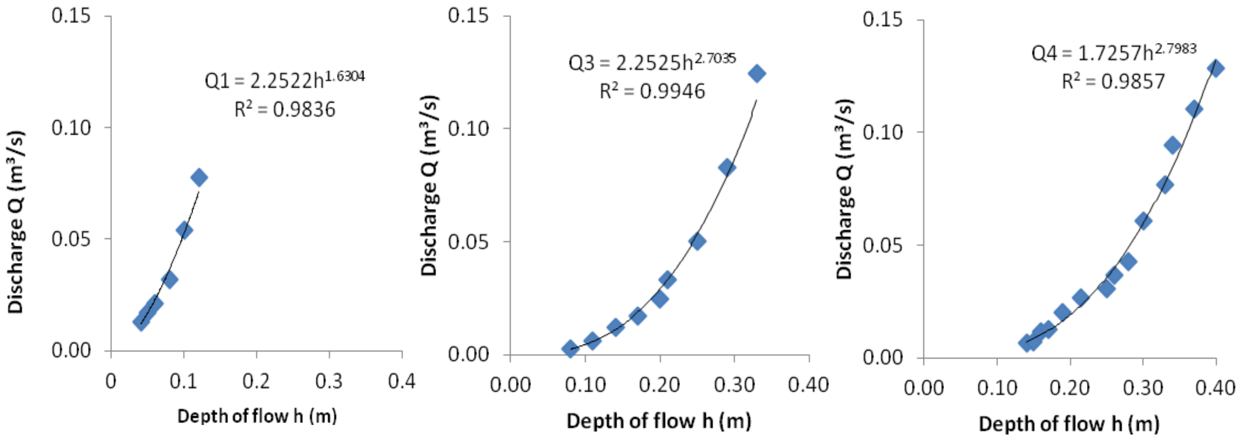


Figure 24. Rating curve for catchments 1, 3 and 4.

3.4.1.2 Manning's roughness coefficients

The roughness coefficients n for all catchments are calculated using eq. 14 (Table 10). The photographs of the outlets on which the collective group estimations are based together with the estimated values for the parameters defined by Cowan (1956) are presented in Annex 18.1 and Annex 18.2. Over all study areas, n ranged from 0.043 (catchment 9) to 0.123 (catchment 8) and the mean n is 0.068 (± 0.123). Catchment 8 has vegetation and big boulders inside the outlet channel unlike the other catchment outlets, which is reflected by its exceptionally high roughness coefficient. As a lower standard deviation does not mean less variable data, the coefficient of variation (CV) is calculated per parameter as the ratio of the standard deviation to the mean. In this way the variance for each estimated parameter (n_0, n_1,…) can be compared (Annex 18.3). Parameter n_5, which stands for the meandering of the channel seems to be the most robust parameter as it has the lowest mean CV (0.124). Also n_0 (material in which the channel is formed) seems to be relatively well estimated with CV= 0.373. Parameters n_3 an n_4 seem to be difficult parameters to estimate with CV= 1.135 for n_3 (presence of obstructions in the cross sectional area) and CV= 1.375 for n_4 (effect of vegetation).

Table 10. Mean estimated parameters by 8 geomorphologists for the roughness coefficients for the outlet of ten subcatchments in Wanzaye (Ethiopia, 2013).

	n_0	n_1	n_2	n_3	n_4	n_5	n
catchment 1	0.037 ± 0.017	0.012 ± 0.005	0.006 ± 0.003	0.017 ± 0.009	0.004 ± 0.004	1.094 ± 0.078	0.083
catchment 2	0.050 ± 0.060	0.008 ± 0.005	0.004 ± 0.002	0.014 ± 0.007	0.007 ± 0.002	1.083 ± 0.103	0.089
catchment 3	0.025 ± 0.000	0.007 ± 0.006	0.002 ± 0.002	0.003 ± 0.007	0.016 ± 0.034	1.038 ± 0.069	0.054
catchment 4	0.023 ± 0.005	0.013 ± 0.007	0.005 ± 0.005	0.014 ± 0.008	0.003 ± 0.005	1.056 ± 0.112	0.060
catchment 5	0.026 ± 0.007	0.013 ± 0.005	0.008 ± 0.004	0.011 ± 0.007	0.003 ± 0.005	1.110 ± 0.105	0.067
catchment 6	0.024 ± 0.010	0.008 ± 0.008	0.003 ± 0.005	0.007 ± 0.007	0.001 ± 0.002	1.038 ± 0.069	0.045
catchment 7	0.020 ± 0.000	0.008 ± 0.007	0.006 ± 0.005	0.013 ± 0.035	0.002 ± 0.004	1.019 ± 0.053	0.050
catchment 8	0.049 ± 0.016	0.008 ± 0.006	0.006 ± 0.005	0.034 ± 0.018	0.015 ± 0.014	1.094 ± 0.078	0.123
catchment 9	0.028 ± 0.009	0.009 ± 0.005	0.004 ± 0.005	0.010 ± 0.014	0.002 ± 0.003	0.806 ± 0.458	0.043
catchment 10	0.032 ± 0.016	0.008 ± 0.006	0.007 ± 0.006	0.019 ± 0.016	0.004 ± 0.004	1.019 ± 0.053	0.071
mean Manning's roughness coefficient							0.068 ± 0.123

With the data in Annex 17 (discharge, cross sectional area, slope gradient at the outlet, hydraulic radius) Manning's roughness coefficients (n) are calculated for catchment 1, 3 and 4 using equation 13. A big difference is observed between these measured roughness coefficients (Annex 17) and the estimated roughness coefficients (Table 10). For catchment 1, the mean measured n is 0.110 (± 0.011) and the estimated n is 0.083. For catchment 3, the mean measured n is 0.124 (± 0.022) which is more than double of the estimated n (0.054). For catchment 4, the mean measured n is 0.032 (± 0.017) which is half of the estimated n (0.060).

3.4.1.3 Runoff and runoff coefficients

Runoff. To use a homogeneous runoff dataset, all runoff analyses are based on runoff data calculated by the rating curves constructed using the Manning formula (Annex 19), which are summarized in Table 11. Runoff was calculated converting the routine flow depths during runoff events by the constructed rating curves (Annex 20). For catchment 8 and 10, the obtained runoff coefficients (RCs) were unrealistic as eleven out of thirteen runoff events for catchment 8, and seven out of eight for catchment 10 show RCs higher than 100%. For this reason, catchment 8 and 10 are excluded for further analyses on runoff.

Table 11. Rating curves based on discharge calculations by the Gauckler-Manning formula (eq. 13) (Manning, 1891) for the ten study areas in Wanzaye (Ethiopia).

catchment	rating curve
1	$Q = 4.8545h^{1.8129}$
2	$Q = 10.243h^{2.6659}$
3	$Q = 8.2758h^{2.995}$
4	$Q = 0.1061h^{1.3807}$
5	$Q = 0.9618h^{1.6475}$
6	$Q = 0.4943h^{1.9589}$
7	$Q = 0.0489h^{1.4143}$
8	$Q = 1.6287h^{1.5521}$
9	$Q = 0.0451h^{1.3476}$
10	$Q = 0.6147h^{1.3089}$

The calculated runoff for all measured daytime runoff events are listed in Annex 20 and summarized in Table 12. Average of the sum of daytime runoff for July 15 to July 31 was 12.95 mm (± 17.11 mm), for 1 to 31 of August 19.41 mm (± 11.97 mm) and from 1 to 4 of September 5.43 mm (± 7.87 mm) for all study areas in Wanzaye. Means will not be compared as the runoff data is divided for different time intervals. Variations in runoff will be discussed by the variation in runoff coefficients. An example for the runoff events measured on August 15 (approximately 15:00) is illustrated by hydrographs in Figure 25. For catchments 1 and 6, data could not have been gathered from the beginning of the runoff event. Maximum discharges for these runoff events ranged from 0.009 m^3/s for catchment 7 to 0.04 m^3/s for catchment 6.

Table 12. Total estimated nighttime runoff and measured daytime runoff in Wanzaye (Ethiopia) for (15-31) July, (1-31) August and (1-4) September (2013).

	(15- 31) July			(1-31) August			(1-4) September		
catchment	sum nighttime runoff (mm)	sum daytime runoff (mm)	total runoff (mm)	sum nighttime runoff (mm)	sum daytime runoff (mm)	total runoff (mm)	sum nighttime runoff (mm)	sum daytime runoff (mm)	total runoff (mm)
1	85.33	32.49	117.82	76.08	15.31	91.39	11.21	10.92	22.13
2	15.08	1.40	16.48	13.44	5.03	18.47	1.98	0.39	2.37
3	114.92	46.81	161.73	102.45	34.95	137.40	15.09	0.00	15.09
4	56.80	4.90	61.69	50.64	14.08	64.71	7.46	4.60	12.06
5	72.87	9.02	81.89	64.96	33.80	98.76	9.57	22.82	32.39
6	54.00	0.41	54.41	45.01	14.47	59.48	6.46	1.14	7.60
7	38.87	3.75	42.61	32.40	7.03	39.42	4.65	1.48	6.13
9	83.01	4.80	87.82	69.19	30.60	99.79	9.93	2.11	12.05
min	15.08	0.41	16.48	13.44	5.03	18.47	1.98	0.00	2.37
max	114.92	46.81	161.73	102.45	34.95	137.40	15.09	22.82	32.39
mean	65.11	12.95	78.06	56.77	19.41	76.18	8.29	5.43	13.73
STDEV	30.83	17.11	45.62	27.59	11.97	38.06	4.07	7.87	9.64

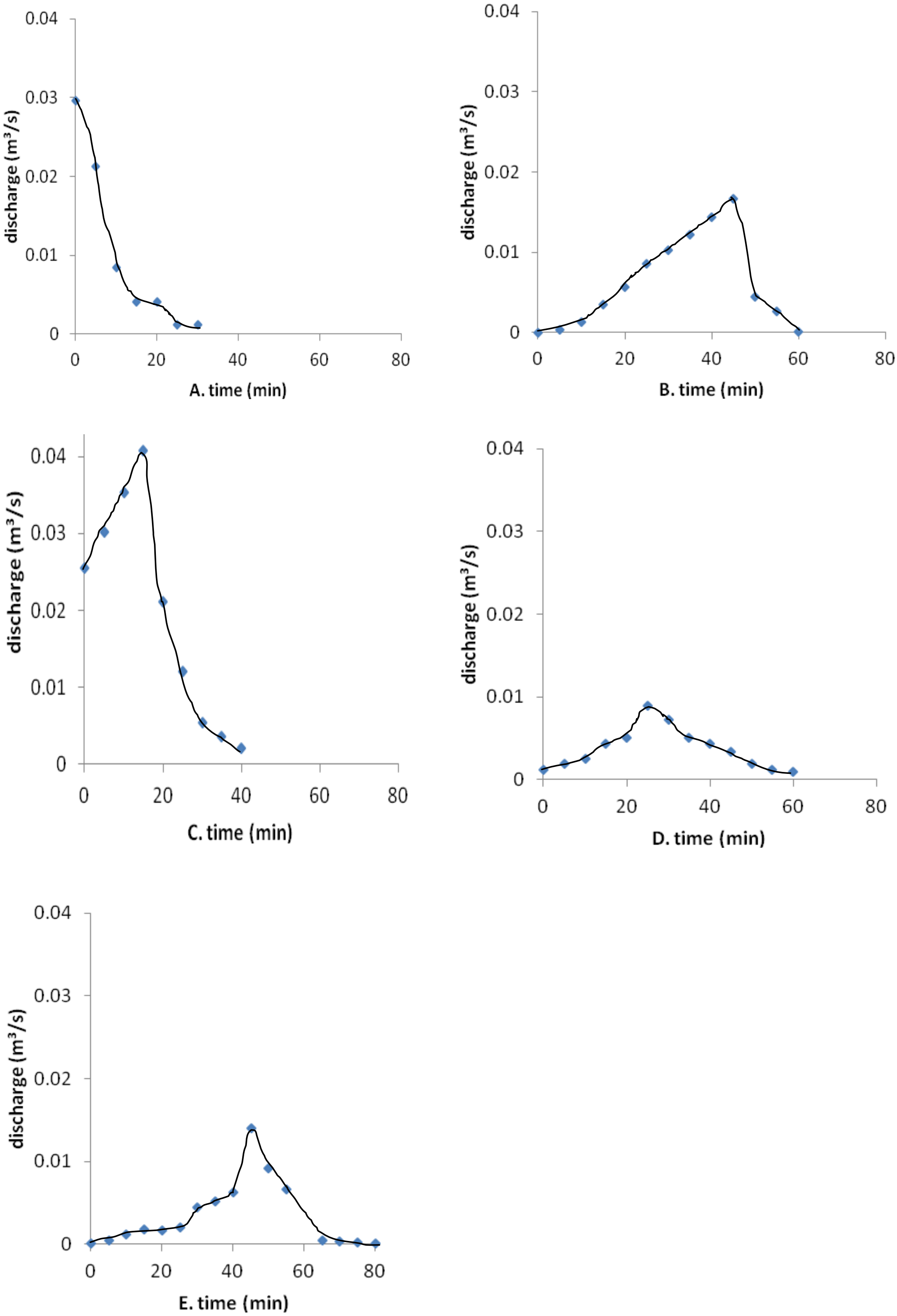


Figure 25. Hydrographs for runoff events measured at the outlets of study areas 1 (A), 2 (B), 6 (C), 7(D), and 9 (E) on August 15 at approximately 15:00 (Wanzaye, Ethiopia, 2013).

Runoff coefficient. Runoff coefficients for all measured runoff events are listed in Annex 20, and summarized in Table 13. Catchment-averaged RCs vary over the ten study areas. A minimum mean RC was found for catchment 2 (5.09%) and a maximum for catchment 3 (38.82%). The mean RC over all study areas is 21.72% (± 9.76%). RC's of catchment 2 are significantly smaller than all other catchments (independent samples t-tests, α = 0.05). Also, significant differences are found between (the first mentioned being smaller) catchment 7 and 1; catchment 4 and 3; catchment 6 and 3; and between catchment 7 and 5.

Table 13. Catchment-averaged RC for the ten study areas in Wanzaye (mean). The following statistics for the catchment-averaged RC are included: number of observations, (n. Obs.), standard deviation (STDEV), minimum (min) and maximum (max). Also the catchment area (ha) is shown.

catchment	mean (%)	n. obs.	STDEV	min	max	area (ha)
1	28.83	16	23.09	0.53	74.16	1.94
2	5.09	16	4.07	0.27	13.70	1.76
3	38.82	13	22.84	14.15	73.63	4.21
4	19.19	13	9.27	4.58	39.62	3.51
5	24.62	17	16.46	5.88	62.89	1.63
6	17.56	11	16.32	2.30	58.97	1.44
7	12.64	12	8.76	2.73	28.56	0.73
9	26.99	12	25.94	1.11	82.83	0.56
mean	21.72					
STDEV	9.76					

No significant (α = 0.05) correlations between RC and the following variables have been found: stone bund density, *feses* density, fraction of barley, fraction of millet, fraction of tef, surface stoniness, soil depth, top width of *feses* right after construction, depth of *feses* right after construction, catchment-averaged slope (°), and *feses* gradient (Annex 21). Although, the following variables are strongly related to the RC: top width *feses* (R= 0.508), depth *feses* (R= 0.607), and *feses* density (R= 0.475). Stone bund density is in contrast to *feses* density negatively correlated with the RC (R= -0.176). Seen the high correlation between RC and top width *feses*, depth *feses*, and *feses* density, these three variables were multiplied to calculate the average volume of *feses* per ha (m^3/ha) with top width as a proxy for the average *feses* width (Annex 11). The correlation (R= 0.38) was found to be not significant (α = 0.05) (Annex 22). By omitting the data for catchment 8 and 10 (N=8, Annex 21), the catchment-averaged slope (°) becomes remarkably highly correlated (R= 0.97, significant for α = 0.01) with the *feses* gradient, whereas these variables were not significantly correlated (R= 0.55, α = 0.05) when data for catchment 8 and 10 were included for analysis (Table 9).

To find variables explaining the differences in RC, a regression analysis with RC as dependent variable and the variables from the correlation matrix (Annex 21) as independent variables is performed in SPSS. A choice between the same independent variables as mentioned for the multiple regression for *feses* density has to be made (assumption of no multicollinearity between the independent variables) because their Pearson correlation coefficient is higher than |0.5|, with additionally: (1) stone bund density - *feses* density, and (2) barley – *feses* density. A first multiple linear regression model was tested for the set of independent variables comprising: *feses* density, soil depth, fraction of tef, top width *feses* right after construction and catchment-averaged slope (°). No linear regression was found as no significant variables ($\alpha = 0.05$) could be entered in the model by the stepwise procedure in SPSS. This was checked by the backward procedure (Annex 23), which consists of first entering all variables into the model followed by a sequential removal of the variables for which the correlation with the dependent variable is the lowest. Another combination of variables was tested in the same way: stone bund density, fraction of tef, soil depth, depth *feses*, and fraction of barley. Yet, no significant variables ($\alpha = 0.05$) were found either (checked by the backward procedure, Annex 24). A last model was tested in SPSS for the variables which were not yet tested in the previous models (because of the assumption of no multicollinearity): surface stoniness, millet, *feses* gradient, *feses* depth right after establishment and *feses* density. The latter was chosen over stone bund density as it has a higher Pearson correlation coefficient for RC. Also, no significant variables ($\alpha = 0.05$) were found (checked by the backward procedure, Annex 25). Curve estimation was performed in SPSS to check if a significant non-linear relation could be found for a model with RC as dependent variable and *feses* density as independent variable. The curve estimation procedure in SPSS produces regression statistics for non-linear models. No significant models ($\alpha = 0.05$) could be found for a quadratic, cubic, logarithmic, inverse or exponential relation. The same results were found for a model with RC as dependent variable and stone bund density as independent variable.

Total runoff. The RCs above are based on daytime manual runoff measurements, whereas no data could be obtained manually during the night. To calculate the total runoff during fieldwork in Wanzaye, a correlation is sought between the daytime runoff coefficients and the daytime rainfall, half day antecedent precipitation, one day antecedent precipitation and five days antecedent precipitation (Table 14). Negative linear relations, i.e. runoff increases when rainfall decreases, are not taken into account as they do not reflect a natural situation. Half of the relations have R^2 less than 0.20, two out of eight have $R^2 \leq 0.40$, one relation has R^2 = 0.56, and for one catchment (catchment 6) only negative relations are found.

Table 14. Linear relations between runoff coefficients (RC) and antecedent precipitation (x) and its coefficients of determination (R^2). Negative relations are marked red, the highest R^2 for positive relations are bold.

catchment	rainfall (mm) fallen that day	half day antecedent rainfall (mm)	1 day antecedent rainfall (mm)	5 days antecedent rainfall (mm)
1	RC = 0.5906x + 22.404	RC = 0.4287x + 21.625	RC = 0.4287x + 21.625	RC = 0.5096x + 24.498
	R^2 = 0.09	R^2 = 0.05	R^2 = 0.05	R^2 = 0.01
2	RC = 0.6711x + 0.6212	RC = -0.0654x + 5.6187	RC = 0.0123x + 4.989	RC = 0.0123x + 4.989
	R^2 = 0.37	R^2 = 0.04	R^2 = 0.00	R^2 = 0.00
3	RC = 0.9432x + 28.954	RC = -0.4685x + 43.022	RC = -0.2849x + 42.762	RC = -0.2636x + 40.67
	R^2 = 0.17	R^2 = 0.05	R^2 = 0.03	R^2 = 0.00
4	RC = -0.652x + 25.775	RC = 0.6582x + 13.321	RC = 0.5436x + 11.498	RC = 0.7641x + 13.84
	R^2 = 0.10	**R^2 = 0.40**	R^2 = 0.33	R^2 = 0.10
5	RC = 2.4519x + 5.2814	RC = 0.0899x + 23.929	RC = 0.1607x + 22.392	RC = -0.2191x + 26.59
	R^2 = 0.56	R^2 = 0.00	R^2 = 0.02	R^2 = 0.00
6	RC = -0.1461x + 18.808	RC = -0.4862x + 21.19	RC = -0.504x + 24.418	RC = -0.2191x + 26.59
	R^2 = 0.00	R^2 = 0.11	R^2 = 0.14	R^2 = 0.00
7	RC = -0.264x + 14.912	RC = -0.0749x + 13.441	RC = -0.028x + 13.153	RC = 0.0277x + 10.161
	R^2 = 0.03	R^2 = 0.01	R^2 = 0.00	**R^2 = 0.01**
9	RC = -0.2393x + 29.964	RC = -0.583x + 31.991	RC = 0.3727x + 21.372	RC = 2.6629x + 9.685
	R^2 = 0.01	R^2 = 0.03	R^2 = 0.01	**R^2 = 0.14**

The variables of antecedent rainfall are thus poor measurements for explaining the variability of the RC, for which it makes no sense to continue calculations of the total runoff based on these relations. Therefore, the relation between RCs and a combination of rainfall fallen the day of the runoff event and antecedent rainfall are examined to see whether a better correlation could be found. This has been analyzed in SPSS by multiple linear regression analysis. Only models for which the “F Change”-value is significant (α = 0.05) would be of interest. The F Change is testing whether the added variables compared to the models in Table 14 represents a significant improvement in the predictive power of the regression model. Only for catchment 4, a significant improvement of the model in Table 14 has been found (Annex 26). Because of these limitations, an estimation of the runoff during the night is made by multiplying the catchment-averaged RC (Table 13) with the nighttime rainfall (Annex 4), which is presented in Table 12. Large variations in runoff are observed between the different study areas. Runoff values are always the smallest for catchment 2. This runoff data will not be used for further analysis as these values are based on rough estimations and because the variation in RC has been analyzed which is a variable of the same parameter (runoff).

Catchment area and development of the rainy season. Using the data from Table 13, a positive linear relation between the runoff coefficient (dependent variable, y) and catchment area (Table 2) (independent variable, x) is found using SPSS: $y = 3.763\,x + 14.295$. Although the relation is not significant ($\alpha = 0.05$) (Annex 27). Also, the runoff coefficients are analyzed in function of time, i.e. in unit of days to express the development of the rainy season, using the data from Annex 20. No significant ($\alpha = 0.05$) linear relations have been found (Annex 28). For this reason we will not group RCs in different time periods (begin, middle, end of the rainy season).

3.4.1.4 Characteristics of hydrographs

Hydrographs are plotted for the measured runoff events for catchments 1, 2, 3, 4, 5, 6, 7 and 9. A relation has been sought for Q_{max}/A as dependent variable and stone bund density or *feses* density as independent variable. A second degree polynomial relation for *feses* density ($R^2 = 0.52$) and a linear relation for stone bund density ($R^2 = 0.12$) are found to have the greatest coefficient of determination compared to other forms of relations (logarithmic, power, exponential) (Figure 26), although both relations are tested in SPSS to be not significant ($\alpha = 0.05$) (Annex 29). Peak discharges rise for *feses* densities up to a maximum at 300 m/ha, after which peak discharges will lower for higher *feses* densities. Peak discharges lower for higher stone bund densities.

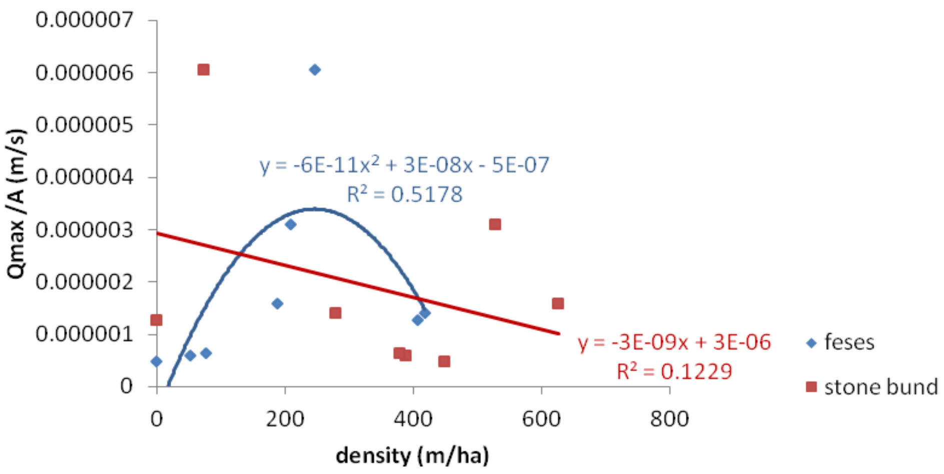


Figure 26. Regression for Q_{max}/A as dependent variable and *feses* density and stone bund density as independent variable.

The calculated kurtosis, VRT and QBT for all measured events are listed in Annex 30 and summarized in Table 15.1. Based on the catchment-averaged values for kurtosis, VRT and QBT a high correlation between these three measures has been found (Table 15.2) (R>0.67). The same trend is visible for the three hydrograph peakedness measures (kurtosis, VRT, QBT): hydrograph peakedness is negatively correlated with stone bund density and positively correlated with *feses* density, although no correlations are significant (α = 0.05) (Table 15.2). A lower value implies a lower hydrograph peakedness for all three measures. Thus, from the data of Wanzaye a possible tendency of a lower hydrograph peakedness for a higher stone bund density and a higher hydrograph peakedness for a higher *feses* density is observed. Also for the normalized peak discharge the same tendency is found with stone bund and *feses* density (Table 15.2).

Table 15.1 Catchment-averaged values for normalized peak discharges (Q_{max}/catchment area (A)) and hydrograph peakedness measures: kurtosis, velocity of rise time (VRT), Q_{max}/base time (QBT).

catchment	*feses* density (m/ha)	stone bund density (m/ha)	kurtosis	VRT ($m^3/(m^3*10^{-3}$ s))	QBT (m^3/s/hour)	Qmax/A (m/s)
1	209	528	0.29	3.08E-07	0.071	3.10E-06
2	0	448	-0.75	5.33E-08	0.019	4.92E-07
3	247	73	0.72	2.79E-07	0.414	6.05E-06
4	53	388	-0.56	4.46E-08	0.017	5.98E-07
5	418	278	-0.23	1.29E-07	0.023	1.40E-06
6	406	0	-0.20	1.07E-07	0.030	1.26E-06
7	78	379	-0.48	5.09E-08	0.008	6.32E-07
9	188	626	0.05	7.67E-08	0.007	1.58E-06

Table 15. 2 Pearson correlation coefficients for the following variables: stone bund (SB) density, *feses* density, kurtosis, velocity of rise time (VRT), Q_{max} over base time, and the normalized peak discharge (Q_{max}/A).

Correlations

		SB_density	*feses*_density	kurtosis	VRT	QBT	Qmax_norm
SB_density	Pearson Correlation	1	-,562	-,228	-,187	-,495	-,350
	Sig. (2-tailed)		,147	,587	,658	,212	,396
	N	8	8	8	8	8	8
*feses*_density	Pearson Correlation	-,562	1	,444	,369	,160	,292
	Sig. (2-tailed)	,147		,271	,368	,706	,483
	N	8	8	8	8	8	8
kurtosis	Pearson Correlation	-,228	,444	1	,862**	,779*	,936**
	Sig. (2-tailed)	,587	,271		,006	,023	,001
	N	8	8	8	8	8	8
VRT	Pearson Correlation	-,187	,369	,862**	1	,679	,861**
	Sig. (2-tailed)	,658	,368	,006		,064	,006
	N	8	8	8	8	8	8
QBT	Pearson Correlation	-,495	,160	,779*	,679	1	,940**
	Sig. (2-tailed)	,212	,706	,023	,064		,001
	N	8	8	8	8	8	8
Qmax_norm	Pearson Correlation	-,350	,292	,936**	,861**	,940**	1
	Sig. (2-tailed)	,396	,483	,001	,006	,001	
	N	8	8	8	8	8	8

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The kurtosis for the individual hydrographs varied for different events and for different catchments. For example: on August 14 (9:00), runoff was measured in catchments 3 and 5. The kurtosis of the hydrograph for catchment 3 is 3.76 and for catchment 5 the kurtosis is 1.22, for which the difference in hydrograph peakedness is illustrated in Figure 27.

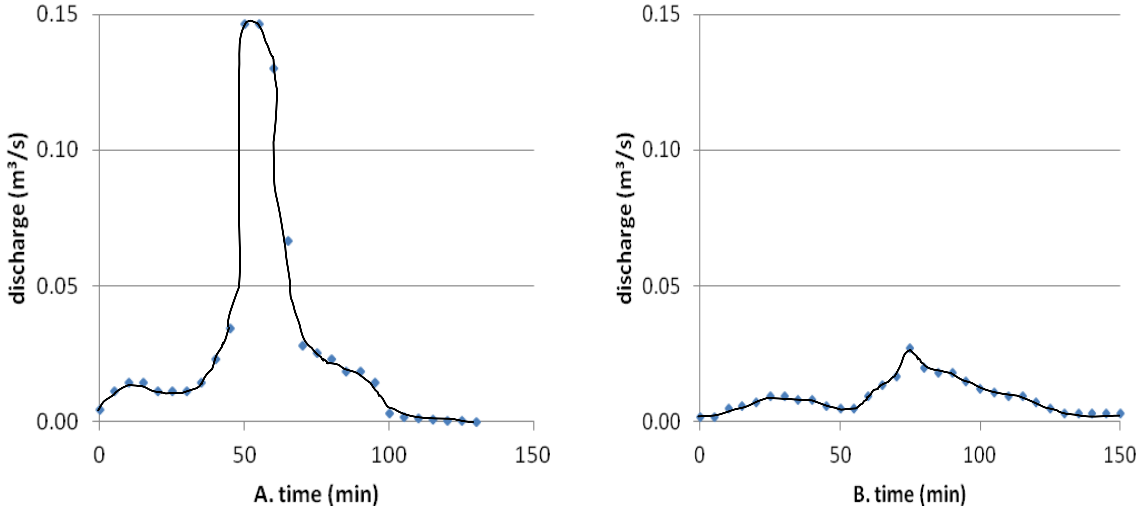


Figure 27. Hydrograph for a runoff event on August 14 (09:00, 2013) measured at the outlet of catchment 3 (A) and catchment 5 (B). The kurtosis of the hydrograph of catchment 3 is higher (3.76) than that of catchment 5 (1.22).

A summary of the calculated kurtosis is presented in Table 16. The lowest catchment-averaged kurtosis is found for study area 2 (-0.75) and the highest for study area 3 (0.72). Using an independent samples t-test in SPSS, no significant differences between the kurtosis means for catchments 1, 2, 3, 4, 5, 6, 7 and 9 are found (α = 0.05). A positive correlation between *feses* density and kurtosis is found (R= 0.444) and a negative between stone bund density and kurtosis (R= -0.228) (Table 15.2). Although both correlations are found to be not significant (α = 0.05), the contrasting correlation values imply a difference of the effect of stone bunds and *feses* on the runoff peak, i.e. higher *feses* density causes higher runoff peaks whereas a higher stone bund density causes lower runoff peaks.

Table 16. Statistics (mean, standard deviation, minimum and maximum) for the kurtosis of the hydrographs of measured runoff events in catchment 1, 2, 3, 4, 5, 6, 7 and 9.

catchment	mean	stdev	min	max
1	0.29	1.66	-2.01	4.32
2	-0.75	2.05	-5.57	4.69
3	0.72	2.26	-2.80	4.74
4	-0.56	1.29	-1.74	3.17
5	-0.23	1.07	-2.08	1.28
6	-0.20	2.05	-2.22	4.52
7	-0.48	0.95	-1.86	1.47
9	0.05	1.88	-1.97	4.95

A relation has been sought between mean kurtosis and *feses* or stone bund density. Values of kurtosis have been summed up by one, so kurtosis would only have positive values, to check if an exponential relation exists. Exponential relations have been found with *feses* density (R^2 = 0.35) and with stone bund density (R^2= 0.05), although both are not significant (α = 0.05) (Annex 31). A second degree polynomial relation for *feses* density (R^2= 0.83) and a linear relation for stone bund density (R^2= 0.05), have the greatest coefficient of determination compared to other forms of relations (logarithmic, power, exponential) (Figure 28). The second degree polynomial relation for *feses* density is found to be significant (α = 0.05), although the linear relation for stone bund density was not (Annex 32).

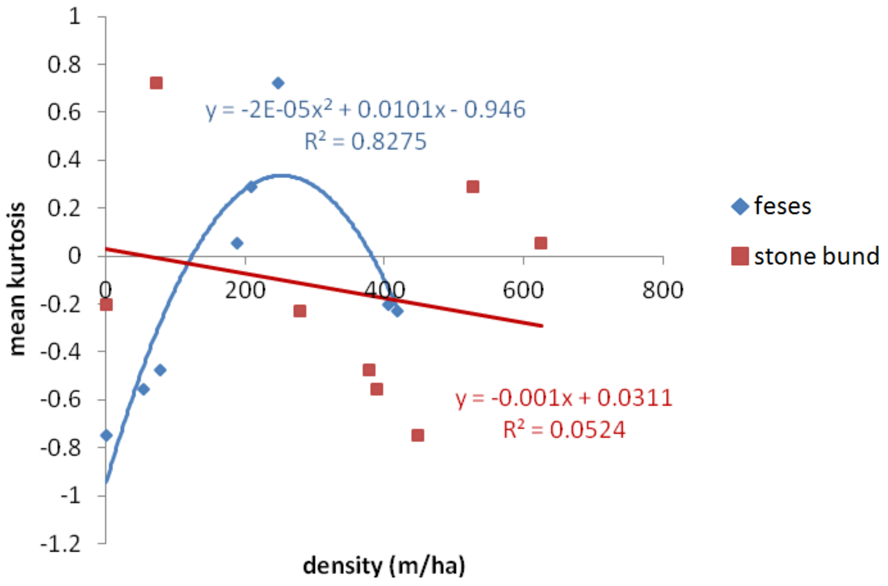


Figure 28. Second degree polynomial relation between kurtosis and *feses* density and a linear relation for stone bund density.

3.4.2 Rill erosion

3.4.2.1 Measured rill erosion and correlations

Dimensions of the measured rills for the ten study areas are listed in Annex 33. Rills which were formed by the misconstruction of stone bunds or *feses* have been categorized. Only situations where the cause of the rill formation was clearly visible in the field, as illustrated in Figure 29 (A. and B.), have been categorized and located on the maps in Annex 34. With 'misconstructed' is meant that water could overflow the *feses*/stone bund and hence create rill erosion. Also rills formed on a thin soil layer or plough pan were visible in the field (Figure 29, C. and D.) but have not been categorized. The total rill volume per area (m³/ha) (TRA) and total soil loss per area (ton/ha), formed by the end of August, vary for the ten study areas (Table 17). A maximum TRA and soil loss per ha has been found for catchment 10 (13.19 m³/ha; 19.66 ton/ha) and a minimum for catchment 2 (0.17 m³/ha; 0.25 ton/ha). The mean volume of rill erosion per ha for all catchments was 3.73 m³/ha (± 4.20 m³/ha) and the mean corresponding soil loss was 5.72 ton/ha (± 6.30 ton/ha). Over all ten subcatchments, 41% of the formed rills were initiated by *feses*, whereas 16% by stone bunds (Table 18). As only rills for which the cause of the rill formation by misconstruction was clearly visible in the field were included, values in Table 18 may be underestimations.

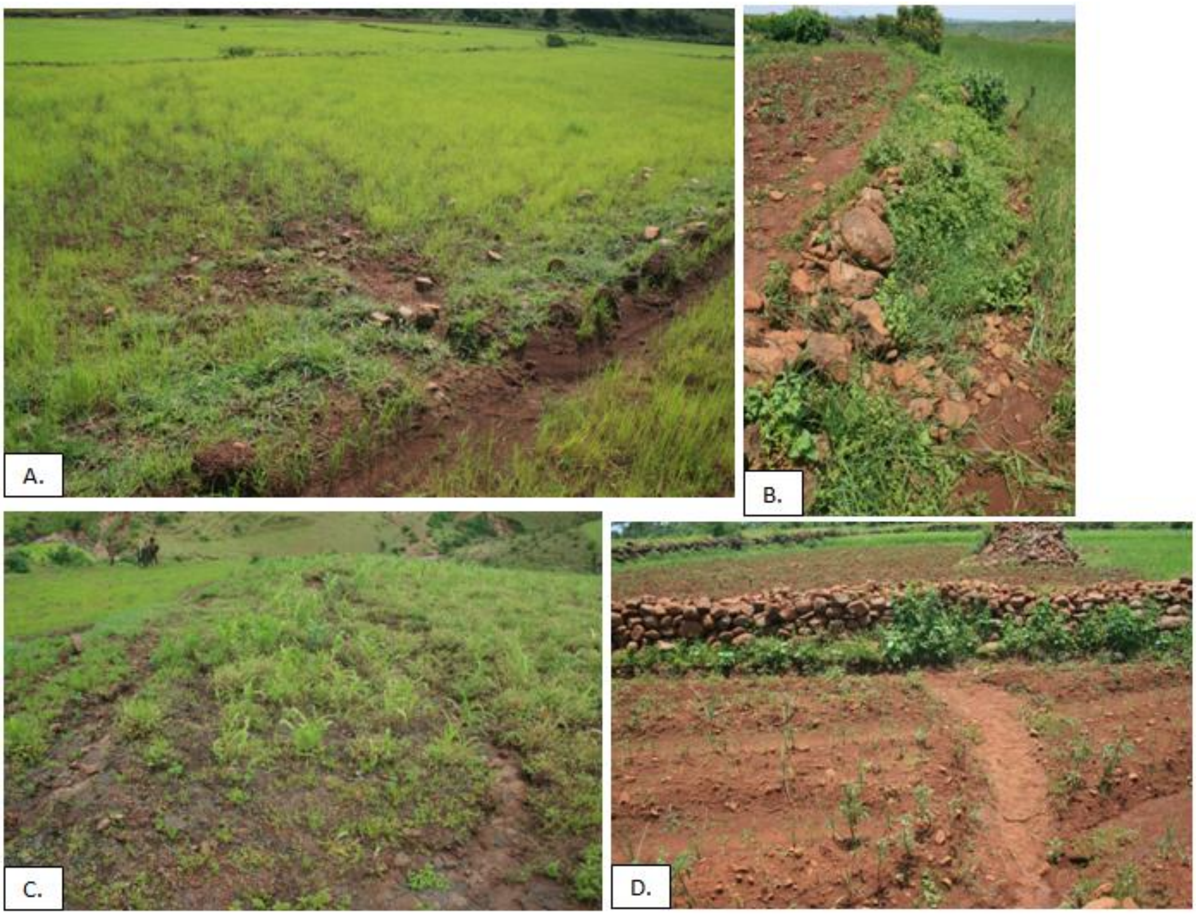


Figure 29. Rill formation originating from *feses* (A) or stone bund (B) and on a thin soil layer (C) or plough pan (D) in Wanzaye (Ethiopia, 2013).

Table 17. Descriptive statistics of the total rill volume per ha (TRA) (m^3/ha) and the total soil loss (ton/ha) for the ten subcatchments.

catchment	TRA (m^3/ha)	total soil loss (ton/ha)
1	0.99	1.58
2	0.17	0.25
3	0.20	0.32
4	0.57	0.89
5	4.01	6.53
6	1.65	2.56
7	7.08	11.68
8	8.34	12.10
9	1.09	1.67
10	13.19	19.66
min	0.17	0.25
max	13.19	19.66
mean	3.73	5.72
STDV	4.20	6.30

Table 18. Amount and fraction of rills originating from misconstructed *feses* or stone bunds.

cause of rill formation	rill count	fraction of all rills (%)
feses	33	41
stone bund	13	16

Although not significant ($\alpha = 0.05$), the correlation between stone bund density and TRA is negative (R= -0.498), whereas the correlation between *feses* density and TRA is positive (R= 0.594) (Annex 35). A strong contrast is found for the correlation between TRA and the fraction of millet or barley, where the former is strongly negative (R= -0.589, not significant at $\alpha = 0.05$) and the latter strongly positive (R= 0.661, significant at $\alpha = 0.05$). No correlation has been found with tef (R=0.060). One other significant ($\alpha = 0.05$) correlation is found with the silt/clay ratio (R=0.635). Other strong correlations, although not significant ($\alpha = 0.05$) are found for the catchment-averaged slope (°) (R=0.544) and soil depth (R= -0.462).

3.4.2.2 Multiple regression for total rill volume

A multiple linear regression for TRA per catchment was tested in SPSS. TRA is the dependent variable and the other variables from the correlation matrix in Annex 35 as listed above are possible independent variables. A choice between the same independent variables as mentioned for the multiple regression of the RC has to be made (assumption of no multicollinearity between the independent variables) because their Pearson correlation coefficient is higher than |0.5|. A first multiple linear regression model was tested for the set of independent variables comprising: *feses* density, fraction of tef, soil depth, top width *feses*, and silt/clay ratio. Only one variable was added to the linear model: the silt/clay ratio (Annex 36.1), whereas the others had been excluded from the model (Annex 36.2). This implies that other variables besides silt/clay ratio do not explain a significant variability for the TRA, giving a simple linear regression (Annex 36.3):

$$TRA = -6.863 + 3.558SC \tag{21}$$

where SC is the silt/clay ratio. Only the coefficient for SC is found significant ($\alpha = 0.05$). The coefficient of determination R^2 for this model is equal to 0.635 (Annex 36.4), implying that the silt/clay ratio explains 63.5% of the variability in the TRA. The same result was found for another set of independent variables, taking into account the multicollinearity: *feses* density, catchment-averaged slope (°), top width *feses* and the silt/clay ratio (Annex 37). A last model was tested in SPSS for the variables which were not yet tested in the previous models (because of the assumption of no multicollinearity): depth of *feses* right after establishment, *feses* gradient, stone bund density, millet and surface stoniness. No variables could enter for this model, which has been checked by the backward procedure.

Curve estimation was performed in SPSS with silt/clay ratio as independent variable and TRA as independent variable to check if a significant non-linear relation could be found. The exponential model was the only model with a significant coefficient ($\alpha = 0.05$), but with a coefficient of determination R^2 lower than model (21) ($R^2 = 0.442$).

3.4.3 Analysis of off-site impacts of land surface management using topographic thresholds

What follows are the analyses based on 26 *feses* catchments, 27 stone bund catchments, and 22 mixed catchments, different from the ten subcatchments on which previous runoff results were based. In Table 19 the following characteristics of these catchments are presented: approximate top width and depth of the gully head, drainage area, surface slope at the gully head and slope gradient at the gully head. The top width and depth of the gully head have been estimated by post-analysis of photographs taken at the gully head. Analyses are based on the filtered dataset, i.e. excluding outliers and catchments with stone bunds younger than 10 years. Based on the catchment area, 4 outliers have been found by the use of the outlier labeling rule (Tukey, 1977; Hoaglin *et al*., 1986). *Feses* catchments are characterized by an area ranging from 0.15 ha to 0.89 ha, with a mean of 0.45 ha (± 0.20 ha) and a mean slope gradient of 0.29 m/m (± 0.12 m/m). Catchments with exclusively stone bunds have an area ranging from 0.31 ha to 2.75 ha with a mean of 1.24 ha (± 0.78 ha and a mean slope gradient of 0.33 m/m (± 0.18 m/m). The selected mixed catchments have areas ranging from 0.28 ha to 2.93 ha with a mean of 1.19 ha (± 0.81 ha) and a mean slope gradient of 0.21 m/m (± 0.13 m/m). The size of all catchments is defined as the drainage area to the uppermost gullyhead.

Table 19. Approximate width and depth of the gully head, drainage area (A), surface slope at the gully head ('slope') and surface slope gradient (s) at the gully head for each unique gully head (GH) for *feses* catchments (a), stone bund catchments (b) and mixed catchments (c). Gully heads for which no photographs have been taken to estimate their width and depth are marked by NA. Attention is drawn to (under 'remarks'): catchments where stone bunds were constructed after 2003 (1), catchments from which the gully head is positioned on a relatively steeper portion of the slope than the drainage area (2), and outliers based on the drainage area (3). The means and standard deviations (STDEV) are calculated by excluding the data from GH marked by 1.

a. ***feses***						
GH number	approx. width (m)	approx. depth (m)	A (ha)	slope (°)	s (m/m)	remarks
a1	NA	NA	0.1487	19.5	0.35	
a2	0.5	0.5	0.1499	10.4	0.18	2
a3	1.5	1.0	0.1815	18.2	0.33	2
a4	3.0	2.0	0.1826	27	0.51	
a5	0.5	1.0	0.2205	10.5	0.19	2
a6	1.0	1.0	0.2355	29.7	0.57	2
a7	2.5	1.5	0.2811	18.7	0.34	2
a8	2.0	1.0	0.3029	16.4	0.29	2
a9	1.0	1.0	0.3284	22.1	0.41	2
a10	1.5	0.5	0.3464	13.3	0.24	
a11	1.0	1.0	0.3766	26.1	0.49	2
a12	NA	NA	0.3966	19.9	0.36	
a13	0.5	1.0	0.4487	8.3	0.15	
a14	NA	NA	0.484	5.2	0.09	
a15	2.0	2.0	0.4879	15	0.27	
a16	1.0	1.0	0.5504	17.1	0.31	2
a17	1.5	1.5	0.5529	7.7	0.14	2
a18	1.5	0.5	0.6049	16.3	0.29	2
a19	NA	NA	0.6062	13.4	0.24	
a20	2.0	1.5	0.6185	14.1	0.25	

a21	2.0	1.0	0.6251	8.7	0.15	2
a22	2.0	1.0	0.6388	21.6	0.4	
a23	NA	NA	0.6934	11.8	0.21	
a24	1.0	0.5	0.7805	18.7	0.34	2
a25	2.0	0.5	0.8903	9.4	0.17	2
a26	1.0	0.5	1.3877	5.2	0.09	3
mean	1.5	1.0	0.4453	16	0.29	
STDEV	0.7	0.5	0.2035	6.2	0.12	

b. stone bund

GH number	approx. width (m)	approx. depth (m)	A (ha)	slope (°)	s (m/m)	remarks
b1	0.5	0.5	0.3089	23.6	0.44	2
b2	1.0	0.5	0.3572	22.5	0.41	2
b3	1.5	1.0	0.4749	38.2	0.79	2
b4	1.0	0.5	0.5271	15.2	0.27	2
b5	1.0	0.5	0.5335	24	0.45	2
b6	1.0	1.0	0.5521	18.7	0.34	1
b7	0.5	0.5	0.6538	4.8	0.08	1
b8	2.0	0.5	0.6554	4.2	0.07	1
b9	2.0	1.5	0.8565	6.4	0.11	1
b10	NA	NA	0.9364	13.5	0.24	
b11	1.0	1.0	0.9774	10.3	0.18	1
b12	0.5	0.5	1.0122	12.4	0.22	1
b13	NA	NA	1.0348	18.8	0.34	1
b14	NA	NA	1.0469	12.6	0.22	
b15	1.5	0.5	1.1338	18.3	0.33	1
b16	1.5	1.5	1.2424	38.9	0.81	1
b17	1.5	1.0	1.3508	21.8	0.4	2
b18	NA	NA	1.3876	25.1	0.47	
b19	1.0	1.0	1.452	11.2	0.2	
b20	1.5	0.5	1.7064	6.1	0.11	1
b21	1.0	0.5	1.9021	23.5	0.44	2
b22	NA	NA	1.9289	18.4	0.33	1
b23	2.0	2.0	2.0998	3.3	0.06	
b24	1.5	0.5	2.2214	9.8	0.17	
b25	1.5	1.5	2.5669	35.9	0.72	1
b26	2.0	1.0	2.7498	6.7	0.12	
b27	NA	NA	4.881	6.3	0.11	3
mean	1.3	0.9	1.2392	17.9	0.33	
STDEV	0.5	0.5	0.778	9.2	0.18	

c. mixed

GH number	approx. width (m)	approx. depth (m)	A (ha)	slope (°)	s (m/m)	remarks
c1	2.0	1.0	0.2821	25.5	0.48	

c2	1.0	1.0	0.307	26.8	0.51	2
c3	1.5	1.0	0.4681	4.7	0.08	2
c4	5.0	1.5	0.5271	16	0.29	
c5	1.0	1.0	0.5601	8	0.14	
c6	2.0	1.0	0.6062	7.1	0.13	2
c7	3.0	2.0	0.6286	10.9	0.19	
c8	NA	NA	0.7355	4.8	0.08	
c9	NA	NA	0.8113	18.3	0.33	
c10	0.5	0.5	0.8302	7.2	0.13	1
c11	2.5	0.5	0.8621	12.3	0.22	
c12	NA	NA	0.863	18.1	0.33	
c13	3.5	2.0	1.282	9.9	0.18	
c14	1.0	1.0	1.4021	5.5	0.1	2
c15	1.0	0.5	1.5335	11.9	0.21	
c16	1.0	1.5	1.9133	5.8	0.1	
c17	0.5	0.5	2.0059	12	0.21	2
c18	1.0	0.5	2.116	6.7	0.12	2
c19	1.0	0.5	2.7675	14	0.25	
c20	NA	NA	2.9296	3.6	0.06	2
c21	5.0	1.5	4.9029	4.9	0.09	3
c22	2.5	1.0	10.1193	10.1	0.19	3
mean	1.9	1.0	1.1895	11.7	0.21	
STDEV	1.4	0.5	0.8136	6.8	0.13	

Drainage area and slope gradient of the soil surface at the gully head were plotted for three different land management practices (Figure 30): (1) the exclusive use of *feses*, (2) the exclusive use of stone bunds, and (3) the combined use of stone bunds and *feses* (mixed). Catchments including stone bunds younger than 10 years (marked in black on Figure 30) were not taken into account for the construction of the topographical threshold. Their corresponding k-values for two constant b-values (0.38 and 0.5) are presented in Table 20. The lowest k-values are found for *feses* catchments, higher k-values are found for mixed catchments, and the highest values for k are attributed to stone bund catchments. The average k-value for the Wanzaye area is 0.131 (± 0,052) for b= 0.38 and 0.123 (± 0,054) for b= 0.5. It should be noted that these values are influenced by the rock fragment content (RFC) of the topsoil (Torri and Poesen, 2014). We found in our study area a mean RFC of 66.7% (± 26.1%) (n = 38).

Table 20. Values of the coefficient k, where b was taken constant for b = 0.38 and b = 0.5 (Eq. 17), for different land management practices: use of drainage ditches (*feses*), stone bunds or a combination of both (mixed). The last column shows the average for all management practices.

	feses	stone bund	mixed	mean
b = 0.38	0.090	0.205	0.099	0.131 (± 0,052)
b = 0.5	0.078	0.198	0.092	0.123 (± 0,054)

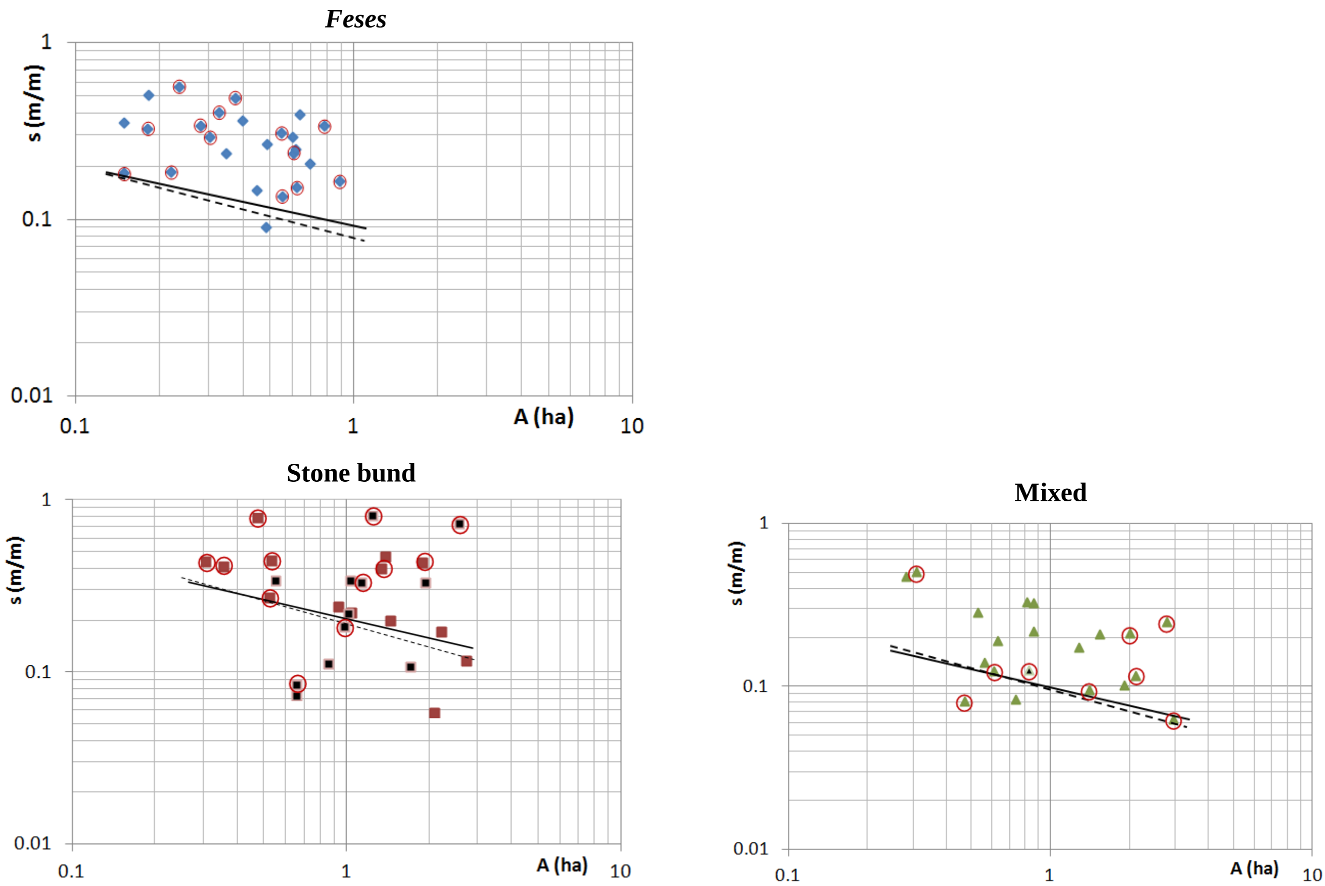


Figure 30. Topographic thresholds for gully heads for different land management practices in Wanzaye (Ethiopia) corresponding to two exponents: b = 0.38 (solid line) and b = 0.5 (dashed line) (Eq. 17). Circled data points refer to catchments for which the slope on which the gully is formed is much steeper than the slope of the catchment. Data points in black represents the catchments including stone bunds younger than 10 years. Bothe these types of catchments have not been used for analysis.

The different catchment types constitute different populations (Table 19, Figure 31) regarding the means of the catchment area, which was statistically validated by an independent samples t-test ($\alpha = 0.05$). The area of *feses* catchments is significantly ($\alpha = 0.05$) smaller than that of stone bund or mixed catchments. However, there is no significant difference between the area of stone bund and that of the mixed catchments. The slope of mixed catchments is statistically (independent samples t-test, $\alpha = 0.05$) smaller than that of *feses* and stone bund catchments, whereas no statistical difference was found between the slope of the *feses* and of stone bund catchments.

In general, Table 19 and Figure 31 indicate that catchments with exclusively drainage ditches have a small area and occur on steep slopes, whereas stone bund catchments are relatively large, occurring also on steep slopes. On the other hand, large catchments located on relatively gentle slopes seem to be tolerable for the combined use of *feses* and stone bunds.

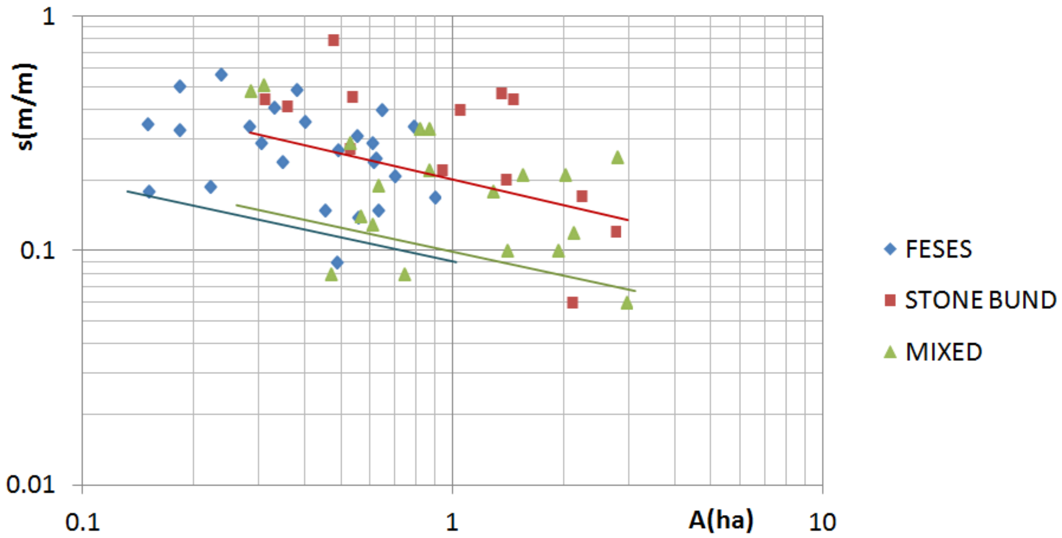


Figure 31. Topographic threshold lines for different land management practices: exclusive use of stone bunds (red), drainage ditches (blue) and a mix of stone bunds and drainage ditches (green). Exponent b (Eq. 17) is set constant at 0.38.

4. DISCUSSION

4.1 Soil and topographical characteristics

4.1.1 Changes in bulk density and soil moisture

Bulk density values for the ten study areas ranged from 1.31 g/cm³ to 1.74 g/cm³ and a total average bulk density was found to be 1.56 g/cm³ (± 0.11 g/cm³), which is high compared to bulk density values from other studies in Ethiopia (Descheemaeker *et al.,* 2006; Mekuria *et al.,* 2007; Nyssen *et al.,* 2000). This high bulk density can be attributed to different factors: (1) samples are exclusively taken in cropland (Lepsch *et al.*, 1994; Lemenih *et al.*, 2005), (2) the local sow method, consisting of seedbed preparation by animal trampling to promote germination (Kuru, 1978; Shiferaw, 2012) (Figure 32), (3) multiple tillage operations (Carter, 1990; Nyssen *et al.*, 2000), and (4) type of clay minerals and soil moisture content (Kamara & Haque (1987). The latter is illustrated in Figure 21, where bulk density values of approximately 2.00 g/cm³ are reached for soils in Ethiopia with a moisture content around 25% (Kamara & Haque (1987). Wanjogu *et al.* (2006) found bulk density values ranging from 1.24 g/cm³ to 1.58 g/cm³ on cropland in Kenya, for which higher bulk density values were caused by trampling of livestock. Koul & Panwar (2012) explained the bulk density values found in India ranging from 1.21-1.55 g/cm³ by referring to the study of Baruah & Barthakur (1997) who observed bulk density values to be inversely related to tillage intensity. These findings are consistent with the positive correlation we found in Wanzaye between the fraction of cultivated tef and bulk density (R= 0.64, significant at $\alpha = 0.05$, Table 9). Tef requires a fine seedbed and hence a high tillage frequency for tef is common in Ethiopia (Deckers *et al.,* 1998). Nitisols and Luvisols are predominant in the area around Wanzaye (Colot, 2012; Miserez, 2013; Setegn *et al.*, 2009), for which an average bulk density of 1.4 g/cm³ (Luvisols) and 0.8 g/cm³ (Nitisols) have been found in the Lake Tana basin by a recent study of Dile & Raghavan (2014).

Figure 32. Cattle trampling during sowing in Wanzaye (Ethiopia, July 2013).

Kamara & Haque (1987) found a significant (α = 0.05) quadratic relation between gravimetric soil moisture content and bulk density of vertisols in the Ethiopian Highlands (Figure 21). This relation was based on the fact that bulk density decreases when soil moisture content increases due to the presence of swelling clays in the soil (Fares *et al.*, 2004; Fox, 1964; Berndt & Coughlan, 1977; McIntyre, 1984). Such a relation was not found for the data of bulk density and soil moisture content in Wanzaye, which implies that there are no swelling clays present in the study area of Wanzaye. Which makes the fourth assumption explaining the high bulk density measured in Wanzaye invalid.

4.1.2 Evaluation of the erodibility of the area using the silt/clay ratio

A mean silt/clay ratio of 2.97 (± 1.30) for Wanzaye was found, ranging from 1.4 to 5.5 over all study areas (Table 6). A consensus in literature exists on the fact that silt is particularly erodible due to the lack of binding agents (Benett, 1939; Kuron & Jung, 1957; Wischmeier & Mannering, 1969; Le Bissonnais *et al*., 1993; Toy *et al*., 2002). Bonilla and Johnson (2012) confirmed earlier research, finding in Chile a relationship expressing increasing soil erodibility with silt content as silt is the most vulnerable to water erosion. Sukiyah *et al*. (2010) found larger total erosion produced by silt areas than clays in the area of the same geomorphology. They conclude by stating: "the larger the silt ratio the larger the soil erodibility". Other studies use a clay/silt ratio, finally concluding the same: Dickhudt *et al*. (2011) found a significant ($\alpha = 0.05$) negative correlation between the eroded mass and the clay/silt ratio, attributed to the increased cohesivity. This confirmed earlier studies using clay/silt ratios by Dunaway *et al*. (1994) and van Ledden *et al*. (2004).

Values found in literature for silt/clay have been summarized in Table 21, for which clay/silt ratios have been inverted to silt/clay ratios. If we compare our data with Table 21, the silt/clay ratio for our study area is rather high. This implicates that the study area is relatively vulnerable to soil erosion. This is in contrast with other research in the Ethiopian Highlands finding a general low inherent soil erodibility attributed to the high clay and rock fragment (Nyssen *et al*., 2004). Though, rock fragment has nothing to do with silt or clay content, which is also evident in the correlation matrix of Wanzaye (Table 9): there is no correlation between the silt/clay ratio and the surface stoniness (R= 0.01). Our findings are in line with Friedel *et al*. (1996) who found a high silt/clay ratio (3.9) on cropland in a haplic Luvisol region in Germany. A wide range of silt/clay ratios are found in the Lake Tana basin: 0.12-1.8 by a study of Colot (2012) and 0.16-1.52 by Miserez (2013). Colot (2012) states that "[...] the entire range (silt/clay ratios) is present in the study area".

A significant correlation ($\alpha = 0.05$) for the silt/clay ratio in Wanzaye was found with the depth of the *feses*. These depths were measured at the beginning of the fieldwork period in the middle of July shortly after their establishment. Nevertheless, strong rain events occurring before the fieldwork could have already eroded the *feses*, which might explain the positive correlation between the *feses* depth and silt/clay ratio as a high silt/cay ratio indicates a higher erodibility.

Table 21. Values for silt/clay ratios found in litterature. Interpretation refers to the author's interpretation of the silt/clay values. Studies for which only a positive correlation between high silt/clay ratio and erodibility are found, have been indicated as 'positive correlation'. Study areas are listed by latitude. Own results are incorporated in the table.

country	silt/clay	interpretation	author
Germany	3.9	high	Friedel *et al*. (1996)
U.S.A	0.67 (± 0.48)	positive correlation	Dickhudt *et al.* (2011)
U.S.A	/	positive correlation	Dunaway *et al.* (1994)
Israel	0.82-1.47	high	Ben-Hur *et al.*, 1985
	0.13-0.35	low	
India	1.5	/	Singh & Prakash, 1985
Nigeria	0.19-0.29	/	Oti, 2004
Ethiopia (Lake Tana basin)	0.12-1.8	/	Colot, 2012
Ethiopia (Lake Tana basin)	0.16-1.52	/	Miserez, 2013
	Vertisol: 0.50		
	Luvisol: 0.36		
	Nitisol: 0.59		
Ethiopia (Wanzaye, Lake Tana basin)	1.43-5.52 mean: 2.97 (± 1.30)	high	Master thesis Monsieurs, 2014
Central Africa	<0.15	/	van Wambeke, 1962
Kenya	<0.2	very low	Wanjogu *et al.* (2006)
	0.20-0.59	low	
	0.60-1.00	medium	
	>1.00	high	
Indonesia	1.5-1.66	positive correlation	Sukiyah *et al.*, 2010

4.1.3 Relations between soil depth, stoniness and slope

The Ethiopian Highlands have been characterized as very vulnerable to soil erosion, loosing tons of fertile soil (Hurni, 1989; Krüger *et al.,* 1996; Amsalu & de Graaf, 2007). This explains the thin soil layer found on cropland in Wanzaye (Annex 7). Holden & Shiferaw (2000) estimated 21% of the land to be shallow (soil depth < 30 cm) and 48% to be of medium depth (30-60 cm) in a comparable area to Wanzaye (Andit Tid) in the Ethiopian Highlands.

Soil depth is less on steeper slopes (Easton *et al.*, 2010; Hopp & McDonnell, 2009), which is statistically found significant (α = 0.05) also for Wanzaye (R= -0.64, Table 9). Despite the consensus in literature on the fact that surface stoniness protects cropland from soil erosion (Wischmeier & Smith, 1978; Poesen *et al.*, 1994; Nyssen *et al.*, 2001; Nyssen *et al.*, 2007), a strong negative correlation is found in Wanzaye between soil depth and surface stoniness (R= -0.81, significant at α = 0.01). It is more reasonable that this correlation is the result of the underlying correlation between stoniness and catchment-averaged slope (°) (R= 0.67, significant at α = 0.05, Table 9), as we stated already before that thin soils occur on steep slopes. Nyssen *et al.* (2002a) found a mean rock fragment cover in cropland on basalt ranging between 57% (± 3%) and 85% (± 11%), which is in line with the measurements in Wanzaye.

4.2 The use of *feses* as a SWC tool comprising also erosive features

4.2.1 The use of feses in Wanzaye: farmers' perception about the use of feses and observed characteristics

From the observations and the discussions with the farmers, we understand that the establishment of *feses* consists of making a difficult balance between the *feses*' erosive features and its soil protecting features. Confirmed by our observations, farmers perceive the construction of *feses* at a great angle with the contour as a mismanagement of the land whilst the *feses* is eroding deeper. Whereas, a strong negative correlation was found between the angle of the constructed *feses* with the contour and the total volume of rill erosion/ha (R= -0.526, not significant at α = 0.05) (Annex 35), implying that *feses* at a small angle with the contour induces more volume of rill erosion due to overflowing water. This was also confirmed by the count of rills initiated by *feses* (Table 18). Over all monitor sites, 45% comprised *feses* which got deepened, nevertheless 47% comprised *feses* that got sedimented with upslope material (Table 7). Hypothesis 2 is confirmed, stating that drainage ditches will incise over time, although not unilaterally for which we recommend further quantitative research on the development of *feses* during the rainy season. We observed a high positive correlation between the angle of the constructed *feses* with the contour and stone bund density (R= 0.749, significant at α = 0.05, Table 9), whereas this correlation is highly negative for *feses* density (R= -0.671, significant at α = 0.05, Table 9). This implies that if stone bund density is higher, *feses* are established at a greater angle with the contour. In contrary, if *feses* density is higher, *feses* are established at a smaller angle with the contour. This may be due to the fact that stone bunds are perceived by farmers as a good soil and water conservation tool, which makes the area tolerable for *feses* established at a greater angle with the contour. It is remarkable that the gradient of the established *feses* is highly correlated (R= 0.97, significant on α= 0.01, Annex 21) with the catchment-averaged slope (°) only when data from catchment 8 and 10 are omitted. This may be due to the fact that subcatchments 8 and 10 have high catchment-averaged slopes compared to the other study areas. Catchment 10 is even an outlier based on its catchment-averaged slope (using the outlier labeling rule). Hence, no trend with the other data was found, yet a greater dataset comprising more catchments with varying slope gradients could give us more information about the relation between catchment-averaged slope gradient and the gradient of the *feses*. Top width and depth of the *feses*, right after establishment are highly correlated (R= 0.787, significant at α = 0.01).

No inherent landscape elements have been found which explains the variability of the *feses* density for which we recommend further research on a larger scale. The significant (α = 0.05) correlation found between stone bund density and *feses* density (R= -0.72, Table 9) can be explained by the government policy that forbids making *feses* where stone bunds were constructed at governmental initiative to avoid the demolition of the stone bunds by the power of the concentrated water in the drainage ditches. Farmers also expressed that *feses* were not necessary if stone bunds are present. The correlation was expressed in a linear regression (equation 20). Yet, *feses* are perceived as the best physical conservation technique when stone bunds are lacking, to (1) prevent the loss of seeds, (2) to prevent soil loss by runoff and (3) to evacuate the excess of water. For this reasons, the need of stone bunds is expressed by most farmers in Wanzaye. *Feses* density and soil depth are negatively correlated (R= -0.395, not significant at α = 0.05, Table 9), which can be attributed to the fact that soil depth affects the water retention properties (Kassa *et al.,* 2010) as shallow soils get saturated more quickly causing runoff by saturation excess (Martinez-Mena *et al.,* 1998; Liu *et al.,* 2008). Hence we assume that *feses* are established to avoid a saturated topsoil on shallow soils.

Farmers stated that *feses* were established unrelated to the cultivated crop. Indeed, no significant (α = 0.05) correlations were found between crops and *feses* density, although a positive trend with the fraction of cultivated barley and *feses* density was found, whereas this trend is negative for the fraction of both millet and tef (Table 9). A maximum *feses* density is found for green pepper and onions (372 m/ha) and the second highest *feses* density was found in tef (270 m/ha). In Wanzaye, the positive effects of drainage ditches are perceived to be dominant over their negative impacts which explains the wide implementation of *feses.* Yet, this is only based on a short-term perception.

4.2.2 The use of feses in other areas

In northern Thailand as well as in other parts of Ethiopia, drainage ditches are found to be established by the local plow (Turkelboom *et al.,* 2008; Shiferaw, 2002; Zegeye *et al.,* 2010; Million, 1996; Gessesse, 2014), which is conform to the way of constructing and *feses*' dimensions in Wanzaye. Drainage ditches in other parts of the world can be constructed with bigger dimensions. As for example in the Roujan basin in France, drainage ditches are 0.7 m to 1.2 m wide and 0.8 m to 1.4 m deep (Moussa *et al.,* 2002) and in southeast England ditches' widths ranged from 3.28 m to 3.90 m and depths from 0.76 m to 0.84 m (Watson & Ormerod, 2004). Also in other parts of Ethiopia, topography is a determining factor for the construction of the drainage ditches as the topography controls where water is accumulated (Million, 1996; Gessesse, 2014). The reasons for constructing *feses* mentioned by Million (1996), Gessesse (2014) and Shiferaw (2002) are the same as for Wanzaye.

Traditional drainage ditches are perceived as indigenous SWC practices in Ethiopia (Million, 1996, Zegeye *et al.;* 2010, Shiferaw, 2002; Herweg & Ludi, 1999). Although not stressed by the farmers, soil erosion such as gullying caused by drainage ditches did occur (Million, 1996). Million (1996) concludes by stating that drainage ditches are not a useful SWC tool, but a simple drainage technique imposing severe erosion hazard on steep slopes although cultivated fields without drainage ditches were seriously affected by rill erosion. Hence, a final balance of the positive or negative effects of *feses* on erosion was not clear. A recent similar study by Gessesse (2014) in the Lake Tana basin is also cautious about drawing conclusions on the use of drainage ditches. Statements on erosion features by Gessesse (2014) are always mentioned with caution: "unless there is a proper construction of the drainage ditch…", acknowledging the fact that drainage ditches also provide protection against erosion when properly constructed (i.e. no excessive ditch gradients, proper depth). Farmers do not perceive traditional ditches as risks to erosion problems whilst the collected water is drained to common areas and the erosion features are not visible forms of erosion (Gessesse, 2014). This is also true for farmers in Wanzaye.

It is emphasized that *feses* are particularly useful in cropland with tef (Shiferaw, 2002; Million, 1996; Gessesse, 2014), although this was not confirmed by farmers in Wanzaye and the measured correlation between the fraction of tef and *feses* density (R= -0.262, not significant at $\alpha = 0.05$, Table 9). Other studies on drainage ditches did not emphasize any relation with crops. The combined use of stone bunds and *feses* is not exclusive for Wanzaye. Reij *et al.* (1996) state that for regions with annual rainfall approaching 1000 mm or more, combinations of SWC (for example stone bunds) and drainage ditches in farm fields with a risk of waterlogging, are common (for example in the Mandara mountains, North Cameroon). In Wanzaye, conflicts between neighboring farmers regarding *feses* did not reach dimensions as discussed by Smit & Tefera (2011). Most of the catchments comprise farmers who are related with each other or just wanted to live in peace. If conflicts occurred, they were directly resolved by the local authorities.

4.3 Impact of land surface management on erosion processes

4.3.1 Land surface management and its impacts on runoff

4.3.1.1 Difficulties using the Manning's roughness coefficients

Manning's roughness coefficients (n) estimated for ten study areas in Wanzaye ranged from 0.043 to 0.123. This is similar to the roughness coefficients measured by Jarrett (1984) in a typical high-gradient mountainous stream at Lake Creek (Colorado) ranging from 0.056 to 0.098. Bates *et al.* (1996) used n= 0.05 for a mountainous stream with a rocky bed, which falls also in the range measured in Wanzaye. Manning's roughness coefficients are sometimes visually estimated using calibrated pictures (Barnes, 1967; Hicks & Mason, 1998), although such calibrated pictures were not found for similar channels as in Wanzaye.

Big differences are observed between the measured roughness coefficients (Annex 17) and the estimated roughness coefficients (Table 10). Also, catchment 8 and 10 have been excluded from the runoff analyses as the runoff calculated by the (estimated) Manning formula were unrealistic. This raises questions about the application of the Manning formula for similar environments as Wanzaye. Sources of error using Manning's roughness coefficient (n) are discussed by Jarret (1987): "values of n are much greater on steep-gradient boulder-bed streams than on low-gradient streams having similar relative roughness values". As stream slope increases, turbulence increases, resulting in increased energy losses (Barnes, 1967; Jarret, 1984) for which the effect is not well captured by the roughness coefficient. This has been confirmed by Costa & O'Connor (2013) who state that the assumption of constant flow resistance at all flow depths is a source of error. These observations may explain the erratic calculated runoff for catchment 8 and 10 using the estimated Manning's roughness coefficient, as their corresponding slope gradient at the outlet are very high (S= 0.51m/m). Nevertheless, errors attributed to the manual velocity measurements, which will be discussed further, may also cause erratic differences between the measured and the estimated roughness coefficients.

4.3.1.2 The application of the Manning formula for constructing rating curves

Differences are observed between the two applied methodologies for calculating discharges: (1) manual velocity measurements (float method) and (2) Manning's roughness coefficient. Differences between coefficients b (eq. 11) have been found for rating curves constructed for catchments 1 (b1= 1.63), 3 (b3= 2.70) and 4 (b4= 2.80) by the first method compared to coefficients calculated by the second method (b1= 1.81; b3= 2.99; b4= 1.38) (Figure 24, Table 11). Either the first method is sensible to errors during manual measurements giving incorrect rating curves, or the second method entails systematic errors linked to the slope gradient of the channel. Another source of error is the fact that a single unit with one area and one wetted perimeter is taken for the outlet channel to calculate the rating curve (Myers, 1987). Another possible way to explain their difference is that the velocity measured by the float method is higher than the average velocity of the total channel flow (Chiu & Said, 1995), for which discharges would be overestimated by the first method. We recommend further research into discharge calculations in small mountainous channels and the evaluation of the use of Manning's roughness coefficients. Regardless which of these two methods is used, it has to be considered that the rating curves have been extended beyond the measured highest flow depths. This implies inherent errors for discharge estimations of stronger runoff events (Sivapragasam & Muttil, 2005). Despite the acknowledged sources of error, the rating curve approach using method (2) enables us to search for trends in runoff related to land surface management.

4.3.1.3 Runoff, runoff coefficients and the derived hydrographs

Catchment 8 and 10 have been excluded from runoff analyses for their unrealistic runoff values (more runoff than precipitation). It could be that this error was caused by an underestimation of rainfall as local events in the catchment area were not all captured at the rain gauge in Tashmender. Although this is not very likely because rainfall was found to be equally distributed over the study area (Table 3), and extreme rainfall events are not likely to occur exclusively in catchments 8 and 10. Possible sources of error are: (1) underestimation of the area contributing to runoff for catchment 8 (4104.51 ha) and 10 (2651.11 ha), which have the smallest measured catchment area of all study areas, (2) a systematic error related to the incapability of the Manning formula for channels with a high slope gradient (as discussed above), (3) erratic field measurements of the slope gradient at the outlet channels of catchment 8 and 10, and (4) erratic field measurements of the routine flow depths.

Raw data on (monthly) runoff (mm) for cropland in the Lake Tana basin is scarce. But the amount of runoff measured in Wanzaye (Table 14) is from the same order of magnitude compared to the study of Descheemaeker *et al.* (2006) in the Tigray highlands (Ethiopia). An average RC for the Blue Nile basin has been estimated by different researchers: e.g. Sutcliffe & Parks (1999) found a RC of 17%, Awulachew *et al.* (2008) a RC of 19%, and Shahin (1988) a RC of 22% which are similar to the average RC for Wanzaye (21.72%). The RC for the Blue Nile basin is high because of the “presence of openfield, large Vertisol areas and much rain” (Nyssen *et al.*, 2010). The mean RC calculated for the Lake Tana basin comprises also floodplains which generate lower RCs (Dessie *et al.*, 2014), thus higher mean RC would be expected for Wanzaye, comprising exclusively cropland. Higher RC would also been expected for runoff by saturation excess in the Lake Tana basin (Awulachew *et al.*, 2008), but it is still an ongoing discussion whether the runoff is generated by saturation excess (Zeleke, 2000) or infiltration excess (Horton, 1933). The mean RC for Wanzaye was also influenced by the local slope gradients, soil texture, land use, vegetation cover, organic matter and rock fragment cover (Feleke, 1987; Mwendera & Mohammed, 1997), which may explain the lower-than-expected mean RC.

SWC activities that have taken place over the last decades have lowered the RCs in Ethiopia (Nyssen *et al.*, 2010). This is also reflected by the RC for catchment 2 which comprises exclusively stone bunds (448 m/ha), resulting in a significantly ($\alpha = 0.05$) lower RC (5.09%, Table 13) than the other catchments. Yet, when stone bunds are combined with drainage ditches, the RC will be higher as we can see for catchment 9 with a mean RC of 26.99%, stone bund density of 626 m/ha and *feses* density of 188 m/ha. Although no significant (α =

0.05) correlation or regression could be found, it seems that a combination of low stone bund density and high *feses* density results in a higher RC, whereas catchments with a high stone bund density and low *feses* density have a lower RC. The high positive correlations (although not significant) between the runoff coefficient and *feses* density and the *feses'* dimensions (Annex 21) indicate that the use of *feses* raises higher RCs. Also underlying factors cause variation in the RC, such as type of growing crop, surface stoniness and the catchment-averaged slope (°) (Annex 21).

No significant (α = 0.05) relations between the RCs and time (development of the rainy season) have been found to confirm hypothesis 5, stating that runoff decreases during the rainy season. The same is true for hypothesis 6 stating that runoff decreases with increasing catchment area, as no significant (α = 0.05) relations were found between RC and catchment area. This may be due to the fact that differences in catchment areas for the study areas in Wanzaye are too small to notice a significant trend caused by runoff transmission losses, lithological heterogeneity, heterogeneous rainfall patterns, evaporation and evapotranspiration (Nyssen *et al.*, 2010).

The study areas have not been manipulated to create ideal research situations to compare different land management, i.e. catchments with exclusively stone bunds or exclusively *feses*. Rather we opted for using real life situations with a variation in stone bund density and *feses* density. As a result, no significant differences could be found between the kurtosis of the hydrographs for the ten study areas. Although the correlations with stone bund and *feses* density and the values of three hydrograph peakedness measures (kurtosis, VRT, QBT) were not significant (α = 0.05), a trend of higher runoff peakedness has been found for subcatchments with a higher *feses* density, confirming hypothesis 3, and a lower peakedness for subcatchments with a higher stone bund density. Higher peak runoff induces higher erosion (Hooke, 1979). Yet, a negative correlation was found between the kurtosis and TRA using SPSS (R= -0.286, not significant at α = 0.05, Annex 35). This has no implications as the correlation is not significant (α = 0.05) and only the volume of erosion by rills have been taken into account, which is not representative for the total amount of erosion.

Relations have been found between normalized peak discharges (Q_{max}/A), hydrograph peakedness (kurtosis) and *feses* and stone bund density. Further research on these relations based on a wider (quantitative) and more precise (qualitative) dataset, is recommended. From the data of Wanzaye, the following possible trends are observed. First of all, peak discharges decrease when stone bund density increases whilst runoff reduces with a higher stone bund density (Herweg & Ludi, 1999; Nyssen *et al.,* 2007). The second degree polynomial relation between catchment-averaged peak discharges and *feses* density is peculiar. Higher peak discharges will be found for higher (artificial) drainage densities, similar to the natural situation for drainage densities (Chorley & Morgan, 1962; Horton 1932, 1945; Gregory & Walling, 1986). On the other hand, it could be that if artificial drainage reaches densities so high that the volume of runoff per drainage ditch relatively lowers to a point similar to a situation where no artificial drainage was applied and hence the peak discharges at the outlet will lower again. The increased storage capacity due to an increase in drainage density may also explain the lower peak runoff (Horton, 1945; Thomasson, 1975). Somewhat similar hypotheses can be made for the hydrograph peakedness in relation to (second degree polynomial) the *feses* density. When drainage densities are higher than a certain value (determined as the maximum value of the second degree polynomial regression), it could be that runoff can be dispersed more over the surface in such a way that runoff will gradually reach the outlet for which the peakedness will lower. This idea was applied in Nothumberland (UK) to reduce flood risk by installing diversion structures in ditches to store high flows (Wilkinson *et al.,* 2010). Because stone bunds have proven their efficiency in capturing and temporarily storing runoff water in a catchment (Gebremichael *et al.,* 2005), the linear negative relation between stone bund density and kurtosis seems obvious for the same reason as the linear relation found with the peak discharge.

4.3.2 Land surface management and its relation to rill erosion

The amount of soil loss calculated for Wanzaye (Table 17) can only be compared with values for exclusively rill erosion, as our values would be underestimations compared to the total soil loss. The total volume of rills per ha are low compared to the study of Bewket & Sterk (2003) on cultivated fields in the northwestern highlands of Ethiopia. They measured 22.5 m^3/ha rill volume for a catchment with gentle slopes and 55.5 m^3/ha rill volume for a catchment with steep slopes. Zegeye *et al.* (2010) found an average soil loss of 27 ton/ ha in the Debre Mewi watershed (part of the Lake Tana basin), while the maximum soil loss found in Wanzaye is 19.66 ton/ha. More comparable values have been found by Awulachew *et al.* (2010) who conducted a Soil and Water Assessment Tool (SWAT) -based runoff and sediment yield model analysis for the Gumara catchment. They produced a map of 18 subbasins in the Gumara watershed for which the averaged sediment yields were presented ranging from 0 to 22 ton/ha/year. Wanzaye is situated in the subbasin producing on average 6 to 10 ton/ha/year. These values are lower than the soil loss we measured in Wanzaye as the values of Awulachew *et al.* (2010) comprise only the soil loss transported by rivers. Nyssen *et al.* (2008) found in the northern Ethiopian Highlands an averaged measured soil loss by sheet and rill erosion on cropland of 9.9 (± 13.2) ton/ha/year, which is below the Ethiopian average, i.e. 42 ton/ha/year (Hurni, 1990). The lower soil loss is most probably related to the high surface rock fragment cover (Nyssen *et al.,* 2008), which is also true for Wanzaye.

This wide range of soil loss by rill erosion found in the Ethiopian Highlands originates from the site specific variables controlling the amount of rill erosion: surface rock content (Nyssen *et al.,* 2001), soil and water conservation (SWC) practices (Zegeye *et al.,* 2010), amount and intensity of rain (Nyssen *et al.,* 2005), soil types (Barthès & Roose, 2002) and geomorphology (Billi & Dramis, 2003) to name a few. For Wanzaye, two explanatory factors explaining the relatively low amount of soil loss by rill erosion are found. First of all, a high surface rock fragment was found in Wanzaye. Second, the applied SWC practices in Wanzaye seem to have a positive effect on the amount of rill erosion. Besides the application of stone bunds in Wanzaye, which is generally perceived as a good management tool for erosion control (Nyssen *et al.,* 2007), also *feses* are used as an indigenous practice for erosion control. Zegeye *et al.* (2010) conclude their research on soil erosion in the Lake Tana basin by stating that *feses* are "generally effective and should be an integral part of any soil and water management practices proposed by soil conservation designers". Hence, both SWC practices in Wanzaye (stone bunds and *feses*) are approved to be good tools against soil erosion, yet a difference between both is emphasized in this study.

Farmers in Wanzaye are aware of the negative impacts of *feses* (i.e. transport of sediment, initiating rill erosion). A strong positive correlation between total rill volume/ha and *feses* density (R= 0.594) has been found. By contrast, a strong negative correlation between total rill volume/ha and stone bund density (R= -0.498) for the ten study areas has been found. Although both correlations are not significant (α = 0.05), it shows a clear distinct trend for both SWC practices: *feses* causing higher rill volumes than stone bunds. This is confirmed by the fraction of rills initiated by *feses* (Table 18) (41%), which is higher than for stone bunds

(16%). Also farmers know this problem of rill initiation, although they conclude that *feses* are still the best way to avoid soil erosion when no stone bunds are present. We conclude by confirming hypothesis 1 and 7 stating that poor drainage management will enhance on-site erosion and that stone bunds are efficient tools for soil and water retention.

Less volume of rill erosion is measured for catchments with a higher fraction of cultivated millet (R= -0.589, not significant at $\alpha = 0.05$), whereas the opposite was found for barley (R= 0.661, significant at $\alpha= 0.05$) and tef (R= 0.060, not significant at $\alpha = 0.05$) (Annex 35). An evident positive correlations between total rill volume/ha and the silt/clay ratio (R= 0.635, significant at $\alpha = 0.05$, Annex 35) has been found, whilst a higher erodibility is related to higher silt/clay ratios as discussed above. A significant linear regression has been constructed, expressing their relation (equation 21).

4.3.3 Lessons taken from the analyses using topographic thresholds

4.3.3.1 Scatter in the dataset

There are several sources of scatter in the dataset inducing a blur of data points in Figure 30. A first uncertainty in the data is the local slope gradient which was defined based on a 30 m x 30 m resolution image. This might not fully capture the specific local slope of the soil surface near the gully head as defined by Nyssen *et al*. (2002b). A second source of scatter is the delineation of catchment area contributing overland flow. This area may change over time due to tillage operations (Takken *et al*., 2001) and other land management interventions, for instance drainage ditch construction may enlarge the catchment area by making a waterway connection with another area. For this reason, we focus more on the small drainage areas when constructing a threshold line, as mentioned above. Also the topographical conditions can bias our data. Regressive erosion of a gully head will stop if it reaches a slope which is too low to develop a gully (Figure 16) (Poesen *et al*., 2003), whereas the gully would have developed further upslope if the slope would have been constant. In this case, the gully would regress until it reaches equilibrium between the slope and the area draining into the gully head, which is smaller than under the first conditions (Figure 33). For these gullies (marked in Table 19 and Figure 30), the steeper portion of the slope was taken into consideration in the analysis of topographical thresholds. Filtering our dataset by excluding catchments with stone bunds younger than 10 years old, reduced the scatter in the dataset (Figure 30).

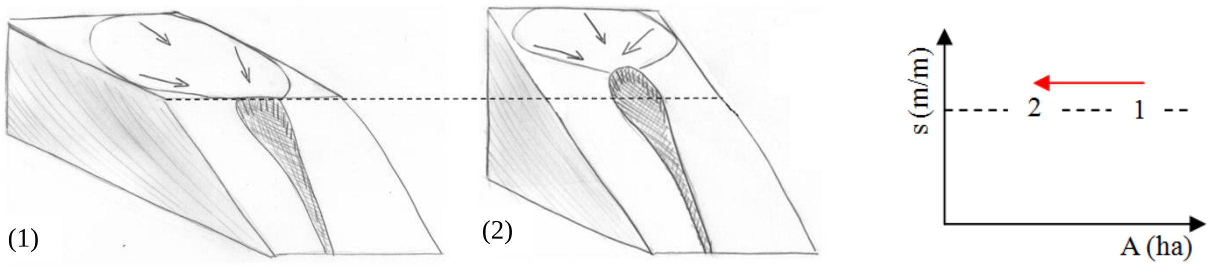


Figure 33. Gully head development under two different topographical conditions. The slope on which the gully is developed can be much steeper (1) or the same (2) as the upslope area. This will create a bias for the topographical thresholds (right). Catchments under the conditions of (1) will generate a data point on the s-A graph located more to the right (bigger area) than when the catchment would have reached equilibrium between the slope and the (smaller) area draining into the gully head under constant slope conditions.

4.3.3.2 Explanatory variables for land management practices

Based on Table 19 and Figure 31 three trends in land management practices are observed: (1) the exclusive use of drainage ditches is rather applied on relatively steep areas for which only a small drainage area is required for the development of a gully head, (2) stone bunds are used on both steeper and gentle sloping cropland, and (3) gentle slopes with large areas seem to be tolerable for the combined use of drainage ditches and stone bunds. These findings correspond largely to the reasons given by the farmers in Wanzaye. Especially on steep areas, conservation practices are needed to conserve the soil's productivity and the farmers agreed that stone bunds are the best conservation practice. Although, when the stone bund construction program of the Ethiopian government has not yet reached a vulnerable place (steep area), farmers are left to the construction of drainage ditches as a conservation practice. In some cases, farmers combine stone bunds with drainage ditches to compensate for the malfunctioning of stone bunds or the bad architecture of stone bunds (no water exit way provided), although this is discouraged by the government as the concentrated water in the drainage ditches may destroy the stone bunds. This may explain why the combined use of *feses* and stone bunds is applied on relatively gentle areas where the concentrated water will not reach the power to destruct stone bunds.

4.3.3.3 Threshold coefficient k for catchments under different land management

As the coefficient k reflects the resistance of an area to gully head development (Torri & Poesen, 2014), we can deduce from Table 20 that catchments with the exclusive use of stone bunds are more resistant to gully head development than *feses* or mixed catchments. Table 20 indicates also that catchments with the exclusive use of drainage channels are relatively the most vulnerable to gully head development. This is illustrated in Figure 31 where we can see that the threshold line for *feses* catchments lies under the threshold line of mixed catchments, which in turn lies under that of stone bund catchments. In this way, hypothesis 4 is confirmed, stating that drainage systems in the upstream fields contribute to gully erosion downstream.

If we compare our findings with the compiled dataset of Torri and Poesen (2014) (Table 22), we can see that for cropland they found k-values of 0.043 (b= 0.38) and 0.037 (b= 0.5), which is roughly one third of what we found: 0.131 (b= 0.38) and 0.123 (b= 0.5). This difference can be explained by the fact that their category 'Cropland' takes areas with no rock fragment content into account. We found in our study area a mean rock fragment content (RFC) of the topsoil of 66.7% (± 26.1%). A correction factor for k-values can be calculated as follows:

$$correctedvalue = \frac{observed}{predicted} = 0.69e^{1.2RFC} \quad (22)$$

(Torri and Poesen, 2014)

Given a correction factor of 1.56 in this case, the k-values from the dataset of Torri and Poesen (2014) come closer to our findings: 0.067 (b= 0.38) and 0.058 (b= 0.5) (Table 16) although they are still only half of the k-values found in Wanzaye. This means that cropland in Wanzaye is relatively less vulnerable to gully head development compared to mean cropland conditions in other regions around the world. We are limited in two ways to compare our data with previous research on topographical threshold conditions: (1) no data are available for different land management practices as 'cropland' has never been differentiated before, and (2) the standardized procedure for topographical threshold analysis is only recently developed by Torri and Poesen (2014).

Table 22. Values of the coefficient k (Eq. 17) for different land use classes for a constant exponent b (i.e. b = 0.38; b = 0.50). N. obs. Is the number of studies from which a threshold s-A could be calculated (Torri and Poesen 2014). Values corrected for rock fragment content (66.7%) are presented between brackets.

		Cropland	Rangeland, pasture	Forest, grassland
b = 0.38				
	Average	0.043 [0.067]	0.154	0.628
	St dev	0.029	0.139	0.318
	Median	0.040	0.085	0.485
	N. Obs	24	18	12
b = 0.5				
	Average	0.037 [0.058]	0.149	0.698
	St dev	0.024	0.144	0.491
	Median	0.030	0.080	0.440
	N. Obs	24	18	12

4.3.3.4 Sedimentation in gullies

In Figure 30 we can see that no gullies were found on land with a slope gradient lower than 6%. This is slightly different from the values found by Poesen *et al*. (2003) in northern Europe on cropland where they found gully sedimentation at slopes gradients ranging from 2% to 4%. When the rock fragment content of the topsoil increases however, the topographically induced sedimentation will take place on steeper slopes (Poesen *et al*., 2002). The critical slope of the soil surface below which sediment deposition in overland flow occurs, taking RFC (66.7%) into account, would be 6% according to data of Poesen *et al*. (2002) from cropland in western Europe, which is similar to our findings.

5. CONCLUSION

5.1 Search for a balance of the effects of drainage on erosion in the Wonzima and Kizin subcatchments

Sloping farmland is susceptible to erosion induced by high rainfall, seasonal soil saturation and the establishment of drainage ditches. Man-made soil drainage has a range of benefits for the farmer's land, although researchers are still divided about the balance of their positive and negative effects. The similarities and interactions between ephemeral gullies and drainage ditches have to be considered to account for all effects of drainage. The use of drainage ditches has both on-site and off-site impacts. Downstream problems comprises increased sediment load, higher peak discharges and gully initiation. Gully erosion appears as a result of the combination of runoff-generating areas (saturated soils), runoff-concentrating features (drainage ditches) and connectivity in the catchment. But few studies deal with the on-site effects of drainage ditches although problems of soil removal and gully initiation are reported. Drainage ditches are a potential source of conflict between neighboring farmers with different interests and power positions. Soil loss due to water erosion is a severe threat to the subsistence rainfed agriculture and the national economy of Ethiopia, for which in this dissertation focus was put on runoff, on-site and off-site erosion processes induced by different land surface management practices.

5.2 Construction and use of drainage ditches and stone bunds

Three main reasons are given by the farmers of Wanzaye for the establishment of *feses*: (1) to prevent the loss of seeds right after sowing by overflowing water, (2) to avoid erosion by uncontrolled runoff, and (3) to drain the accumulated water away from upslope areas. *Feses* in Wanzaye are established at the moment of sowing. As in other parts of Ethiopia, topography is the determining factor for the establishment of the drainage ditches as the topography controls where water is accumulated. The establishment of *feses* consists of making a difficult balance between the *feses*' erosive features and its soil protecting features. *Feses* will not be constructed at the same place as previous year as they would be eroded otherwise. Farmers perceive the establishment of *feses* at a great angle with the contour as a mismanagement of the land whilst the *feses* will be degraded.

The need for stone bunds is expressed by most farmers in Wanzaye. The government policy forbids making *feses* where stone bunds were constructed at governmental initiative to avoid the demolition of the stone bunds by the power of the concentrated water in the drainage ditches. Nevertheless, malfunctioning of stone bunds or an excess of water that needs to be drained away are reasons mentioned by the farmers for the use of both stone bunds and *feses*. A linear regression expressing the relating between both management practices for Wanzaye was found ($R^2 = 0.52$):

$$FD = 408.513 - 0.558\ SB$$

Where FD is *feses* density and SB is stone bund density. *Feses* are perceived to be not necessary when stone bunds are present. No inherent landscape elements have been found which explain the variability of the *feses* density for which we recommend further research on a larger scale.

5.3 The effect of land surface management on runoff

Differences are observed between measured runoff discharges by the float method and calculated discharges using the Manning formula, comprising Manning's roughness coefficient, for which we recommend further research into discharge calculations in small mountainous channels and the application of the Manning formula. Although no significant correlation or regression could be found, it seems that the combination of low stone bund density and high *feses* density results in a higher runoff coefficient (RC), whereas catchments with high stone bund density and low *feses* density have a lower RC. A trend of higher peak runoff has been found for subcatchments with a higher *feses* density, although research with more distinctive field conditions is recommended to search for significant relations. A second degree polynomial relation for kurtosis (expressing hydrograph peakedness) with *feses* density as independent variable and a linear relation with stone bund density as independent variable have been found. Further research on these relations based on a wider (quantitative) and more precise (qualitative) dataset, is recommended. No significant trend for runoff related to the catchment area or the development of the rainy season has been found, for which we recommend further research on a larger scale of time and space.

5.4 On-site effects of land surface management on erosion

Soil loss is low compared to other research results for similar areas in Ethiopia which is most probably related to the high surface rock fragment cover in the area and the applied SWC practices (stone bunds and *feses*). Nevertheless, a distinct trend regarding on-site erosion for both SWC practices has been found: *feses* cause higher rill volumes than stone bunds. Also, it has been observed that poor drainage management initiates on-site erosion and that stone bunds are efficient tools for soil and water retention. A linear relation between total volume of rill erosion per ha (TRA) and the silt/clay ratio (SC) has been found for Wanzaye (R^2= 0.635):

$$TRA = -6.863 + 3.558SC$$

Drainage ditches incise over time, although we recommend further quantitative research on the development of *feses* during the rainy season. Despite farmers' awareness on the on-site erosion caused by *feses*, they perceive drainage ditches as the best conservation practice if no stone bunds are present.

5.5 Off-site effects of land surface management on gully erosion

The practical use of threshold analysis to study the effect of different land management practices to an area's vulnerability to gully head development has been illustrated. Values for coefficient k in the topographical threshold equation can help soil conservationists to identify which land management practices make an area less vulnerable. Three trends in land management for cropland around Wanzaye and the wider region have been observed: (1) the exclusive use of drainage ditches is rather applied on relatively steep areas for which only a small drainage area is required for the development of a gully head, (2) stone bunds are used on both steeper and gentle sloping cropland, (3) gentle slopes with large areas seem to be tolerable for the combined use of drainage ditches and stone bunds. The lowest k-values are found for *feses* catchments, higher k-values are found for mixed catchments, and the highest values for k are attributed to stone bund catchments, which implies that catchments with the exclusive use of drainage ditches are relatively the most vulnerable to gully head development compared to mixed catchments and stone bund catchments. Further research on topographical threshold conditions for different land management practices following the standardized procedure developed by Torri & Poesen (2014) is recommended.

5.6 Evaluation of land surface management in Wanzaye

Finally, based on the research results presented in this dissertation, the following conclusions on land surface management can be made. Drainage ditches cause land degradation through different processes: (1) initiation of on-site rill erosion, (2) concentrated water flow inducing deepening of the channel and soil transport, and (3) concentrated water flow inducing off-site gully erosion. These processes are intensified by the higher peak runoff as an effect of the drainage ditches. Yet, the use of drainage ditches has the advantages of: (1) preventing the loss of seeds right after sowing by overflowing water, (2) avoiding erosion by uncontrolled runoff, and (3) drain the accumulated water away from upslope areas. Stone bunds are found to be efficient tools for soil and water retention. *Feses* are only used as a second-best SWC practice, when no stone bunds are present. These findings have to be taken into consideration when searching for the final balance of the positive and negative effects of the use of drainage ditches on cropland. We are aware that the use of drainage ditches induces a wide range of effects to the croplands productivity which are not exhaustively examined in this dissertation, for which we want to recommend further research on the effects of drainage ditches on cropland, on a larger scale of time and space.

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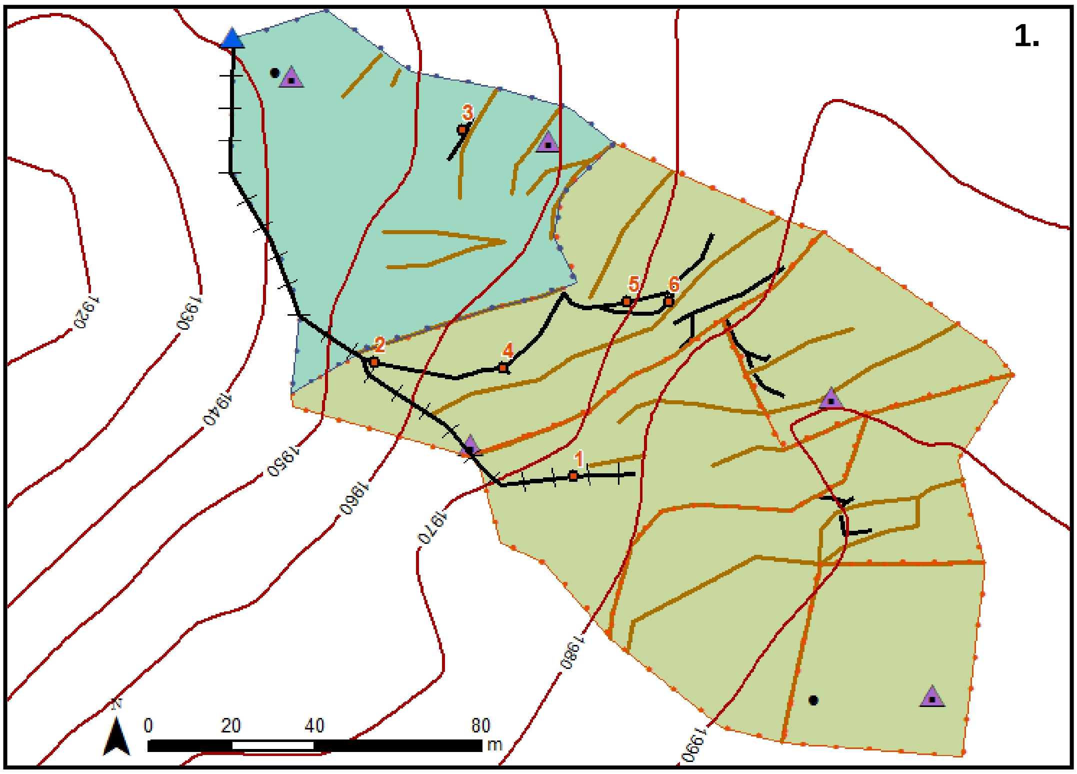
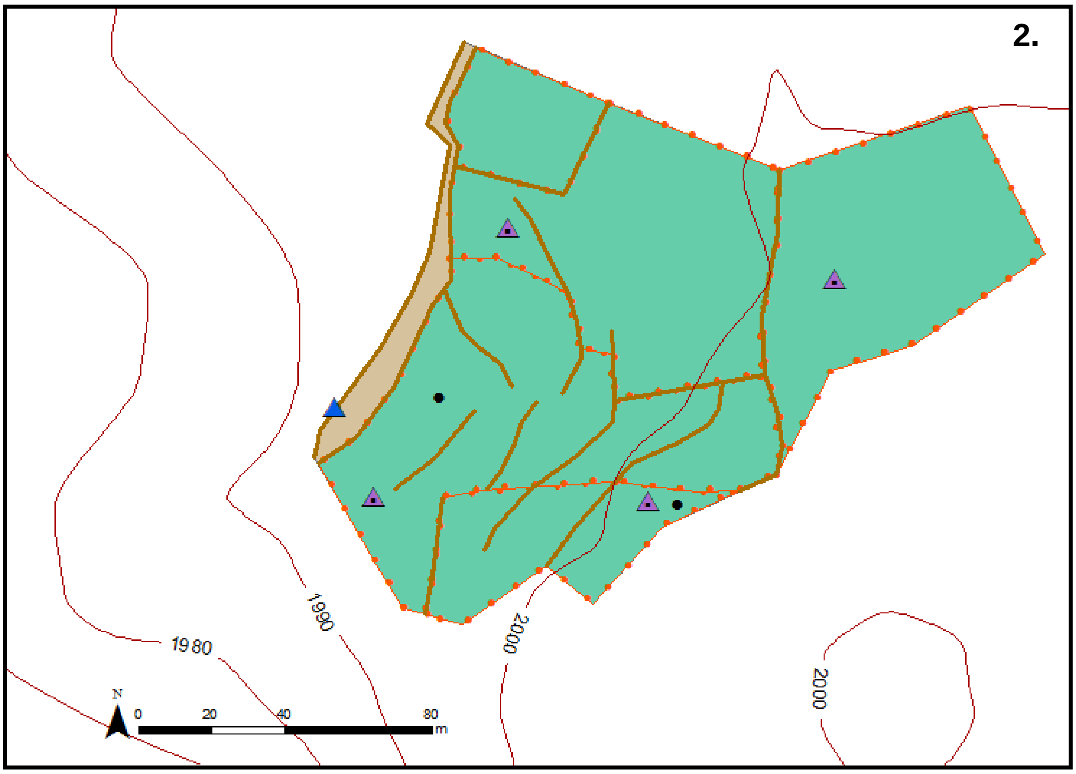
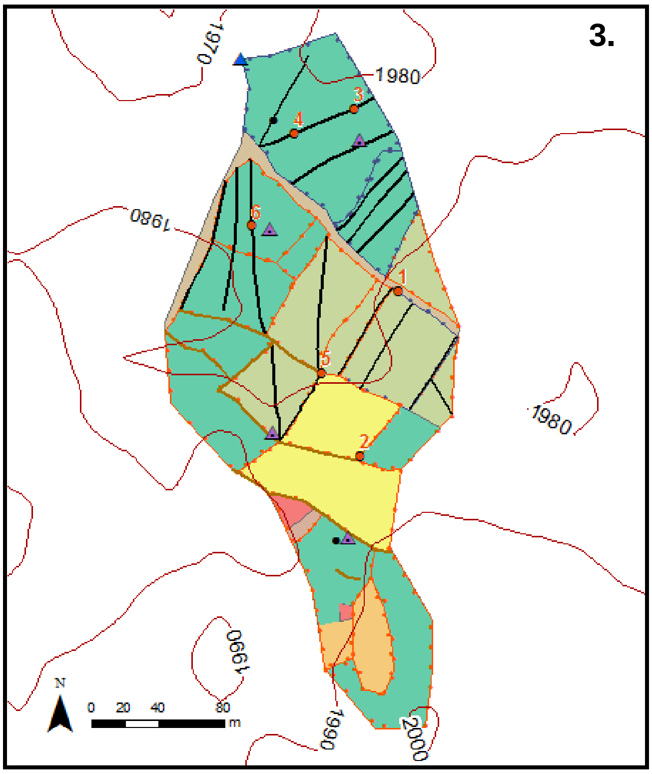
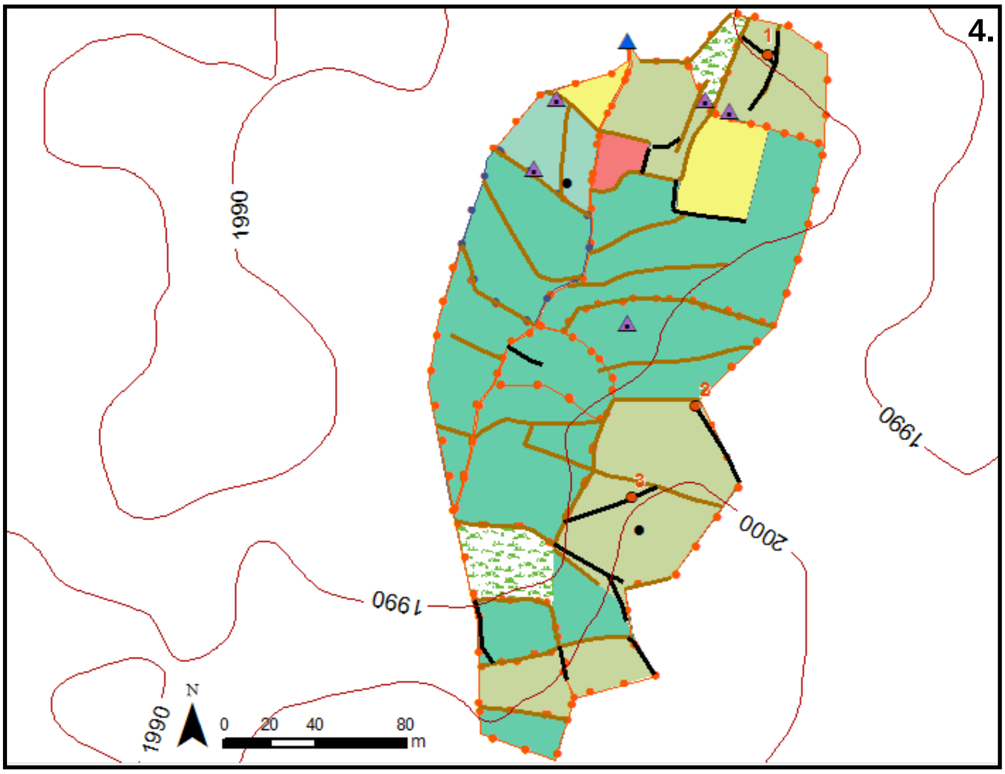
ANNEX

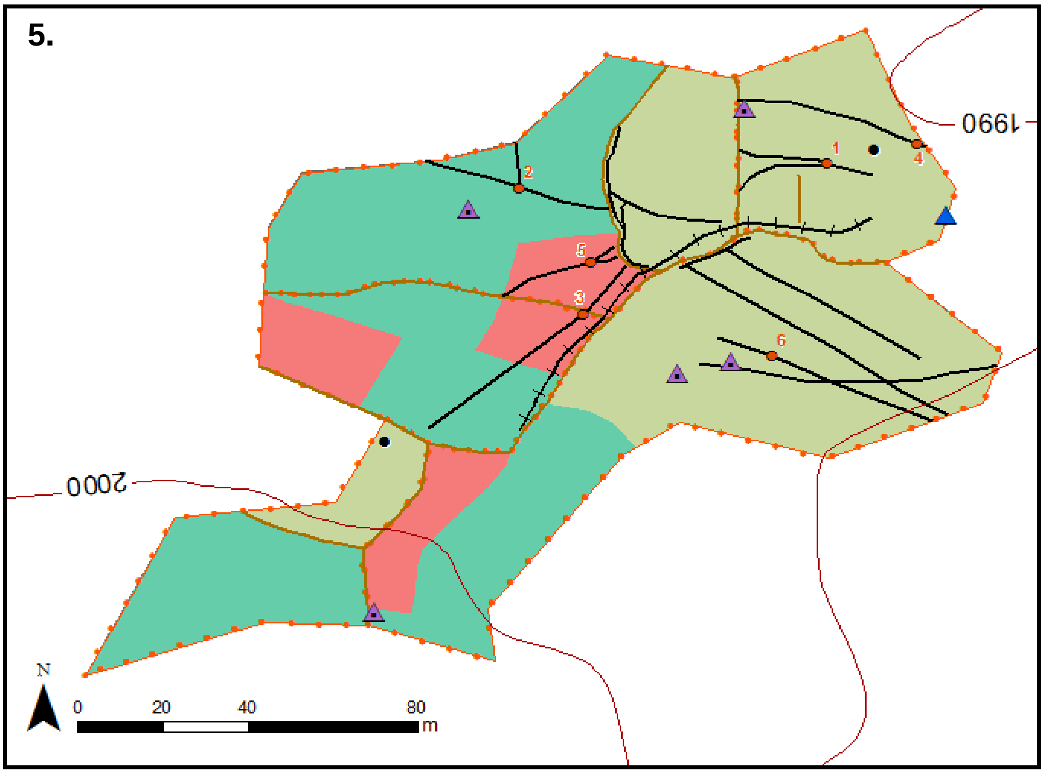
Annex 1. Detailed representation of the 10 subcatchments in the Kizin and Wonzima catchment (see legend on page 158).



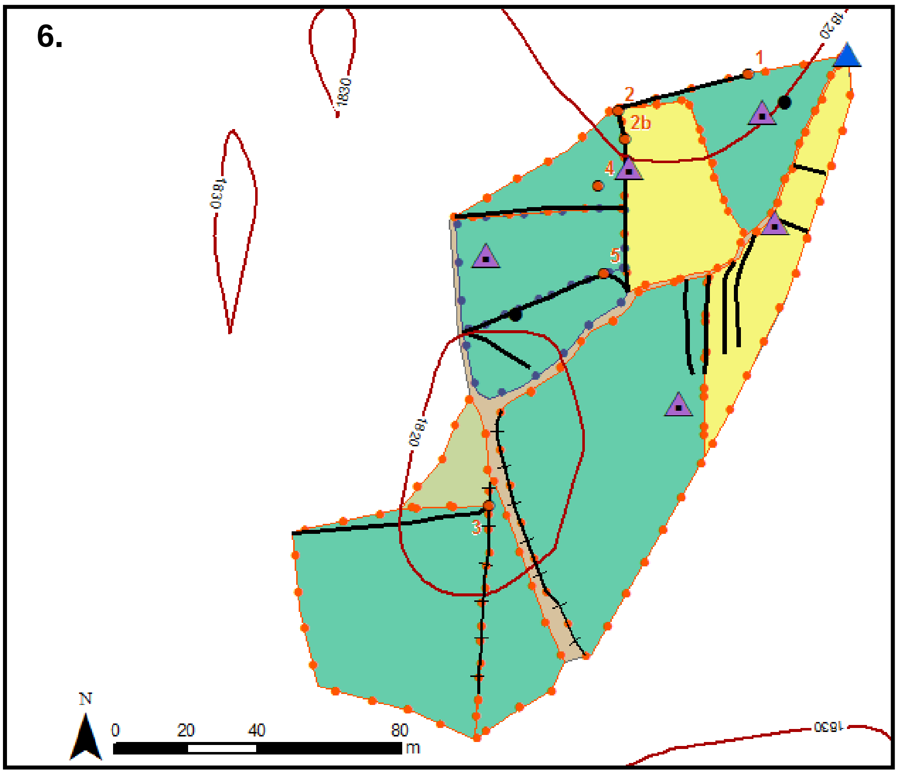



3.
1970
1980
1980
1980
1990
1990
2000
N
0 20 40 80
m

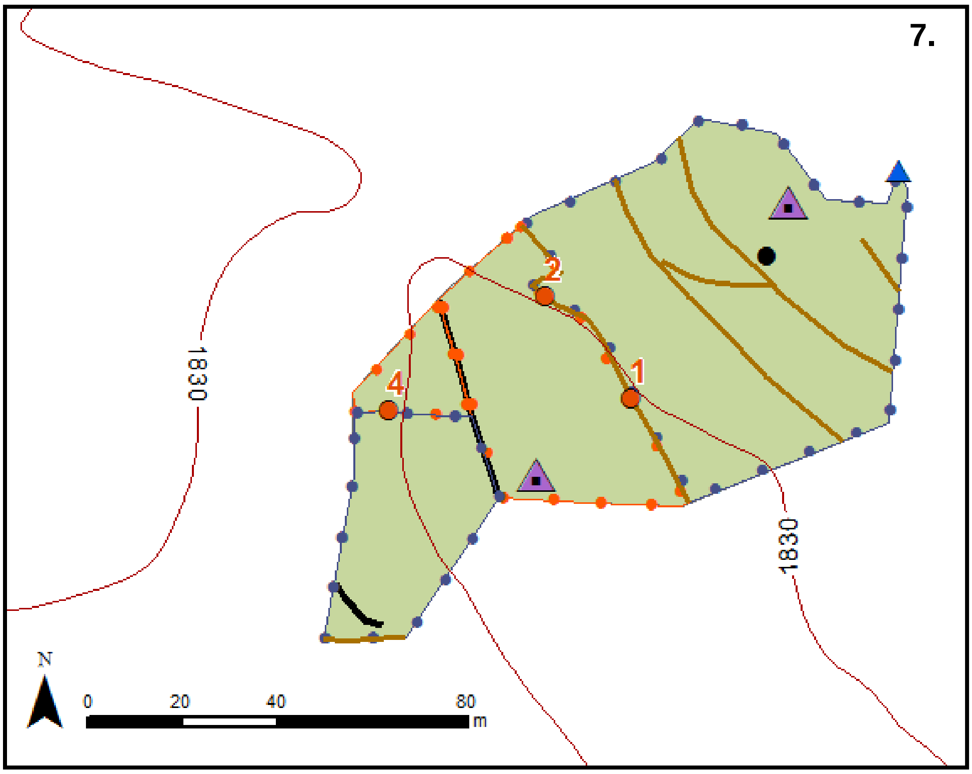

4.
1990
1990
1990
2000
1990
N
0 20 40 80
m

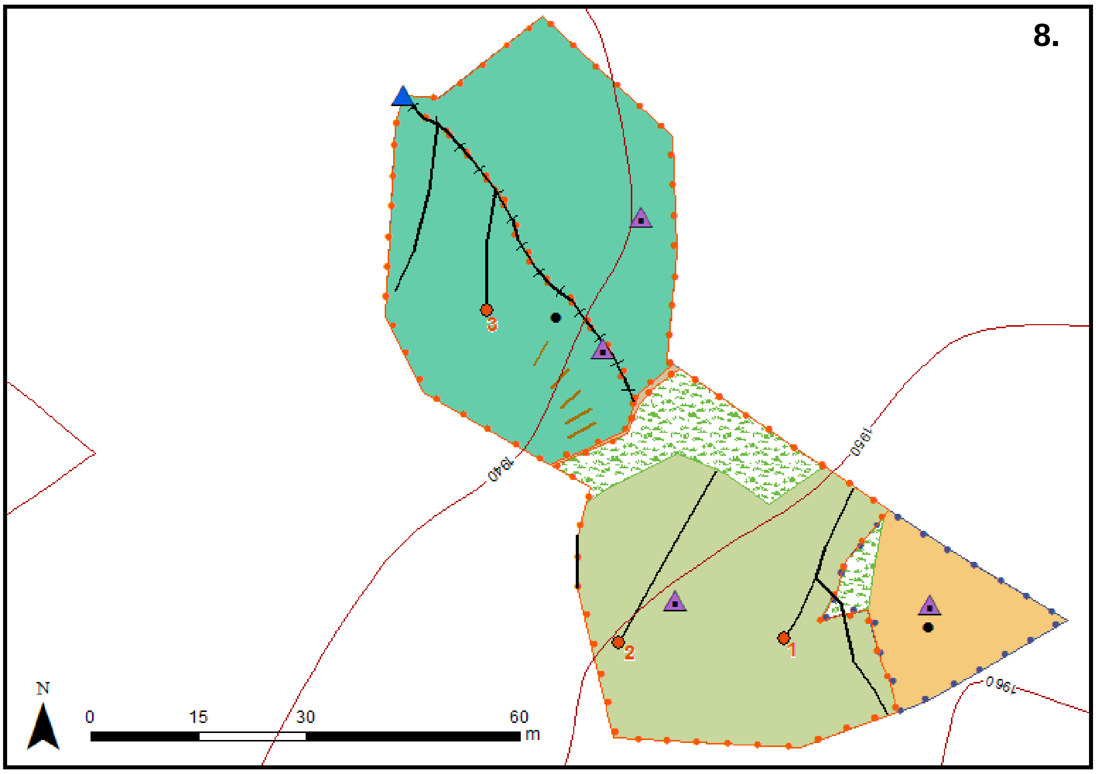


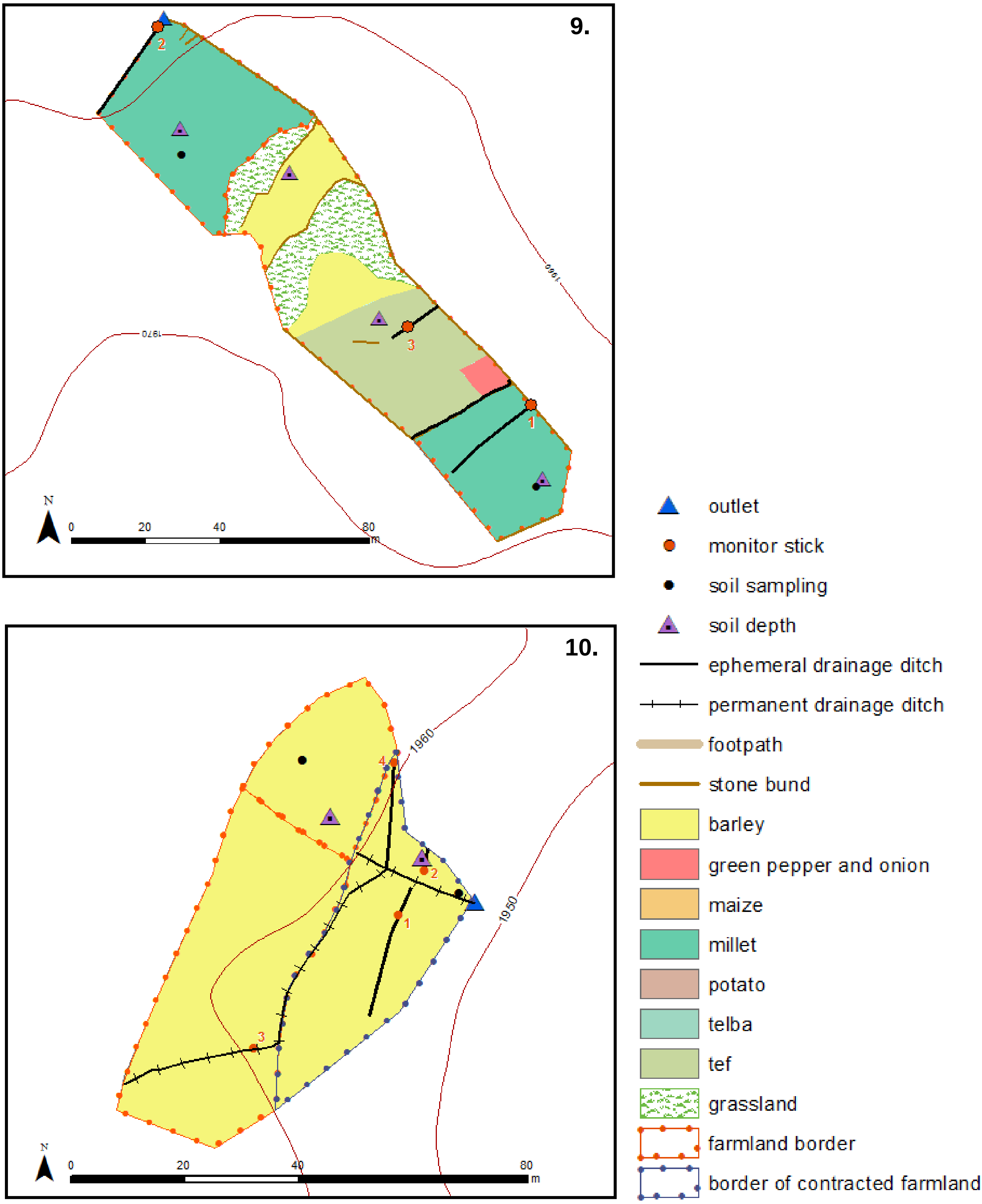
5.
1990
2000
1
2
3
4
5
6
N
0
20
40
80
m



6.
1830
1820
1
2
2b
3
4
5
N
0
20
40
80
m


7.
1830
1830
2
1
4
N
0
20
40
80
m

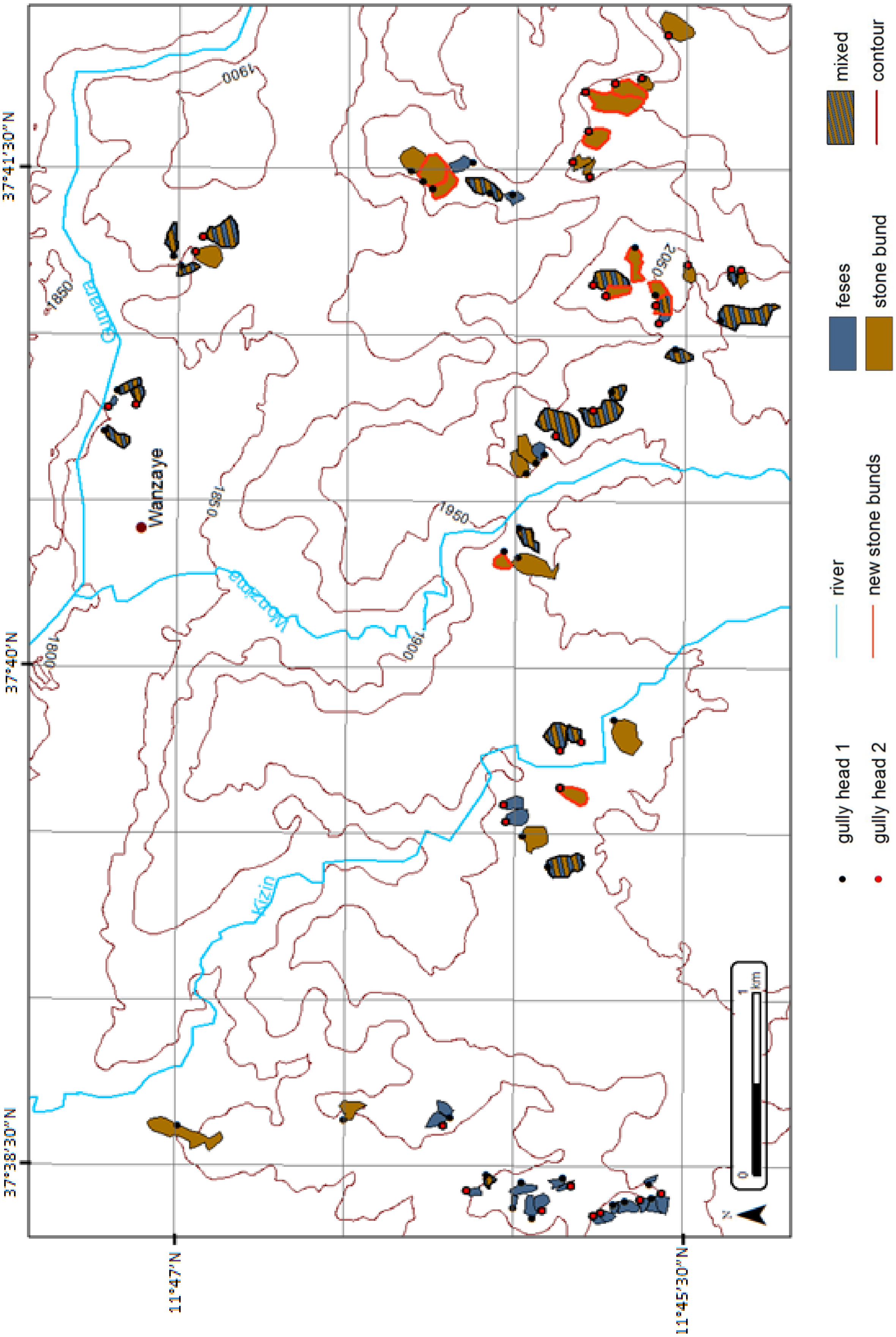

8.
3
2
1
1940
1950
1960
N
0
15
30
60
m


9.
2
3
1
1960
1970
N
0
20
40
80
m
10.
1960
1950
4
2
1
3
N
0
20
40
80
m
outlet
monitor stick
soil sampling
soil depth
ephemeral drainage ditch
permanent drainage ditch
footpath
stone bund
barley
green pepper and onion
maize
millet
potato
telba
tef
grassland
farmland border
border of contracted farmland

Annex 2. Form for calculation of Manning's roughness coefficient (n) adapted from Cowan (1956).

Factor	Description	Recommended value
Material involved (n_0)		
Earth	Bottom/sides of channel composed of soil	0.020
Rock cut	Rock cut in sides of channel	0.025
Fine gravel	Bottom/sides of channel composed of fine gravel	0.024
Coarse gravel	Bottom/sides of channel composed of course gravel	0.028
Cobble	Bottom/sides of channel composed of cobbles	0.030-0.050
Boulder	Bottom/ sides of channel composed of boulders	0.040-0.070
Degree of irregularity (n_1)		
Smooth	Smoothest channel in a given bedmaterial.	0.000
Minor (slight scour)	Having slightly eroded or scoured side slopes.	0.005
Moderate (slumping)	Channels having moderate toconsiderable bed roughness and moderately eroded sides	0.010
Severe (eroded banks)	badlyeroded sides of canals or drainage channels; irregular surfaces of channel	0.020
Variation in channel cross section (location of thalweg) (n_2)		
Gradual	Size/shape of cross sections change gradually	0.000
Alternating occasionally	Cross sections alternate occasionally, or themain flow occasionally shifts from side to side owing tochanges in cross-sectional shape	0.005
Alternating frequency	Cross sections alternate frequently, orthe main flow frequently shifts from side to side owing to changes in cross-sectional shape	0.010-0.015
Effect of obstructions (n_3)		
Negligible	Scattered obstructions occupy <**5 %** of the cross section	0.000
Minor	Obstructions occupy **< 15%** of the cross section	0.010-0.015
Appreciable	Obstructions occupy from **15%** to **50%** of the cross-section	0.020-0.030
Severe	Obstructions occupy more than **50%** of the cross-section	0.040-0.060
Effect of vegetation (n_4)		
None	No vegetation cover	0.000
Low	Grass/weeds	0.005-0.010
Medium	Brush, none in streambed	0.010-0.025
High (young trees)	Young trees	0.025-0.050
Very high	Brush in streams, mature trees	0.050-0.100
Degree of meandering (n_5)		
Minor	Ratio of the channel lengthto valley length is **1.0** to **1.2**	1.00
Appreciable	Ratio of the channel lengthto valley length is **1.2** to **1.5**	1.15
Severe	Ratio of the channel length to valley length is > **1.5**	1.30
Overall equation	$n = (n_0+n_1+n_2+n_3+n_4)*n_5$	

Annex 3. Delineated catchments for analyzing topographic threshold conditions. Catchments marked in red comprise stone bunds younger than 10 years and are not further used for topographical threshold analysis as the related downstream gully is not in phase with the current land management. 'Gully head 1' represents the gully heads for catchments for which the gully is formed at the same slope as the catchment draining in the gully, whereas 'gully head 2' represents catchments for which the gully is formed on a steeper portion of the slope than the catchment draining in the gully.

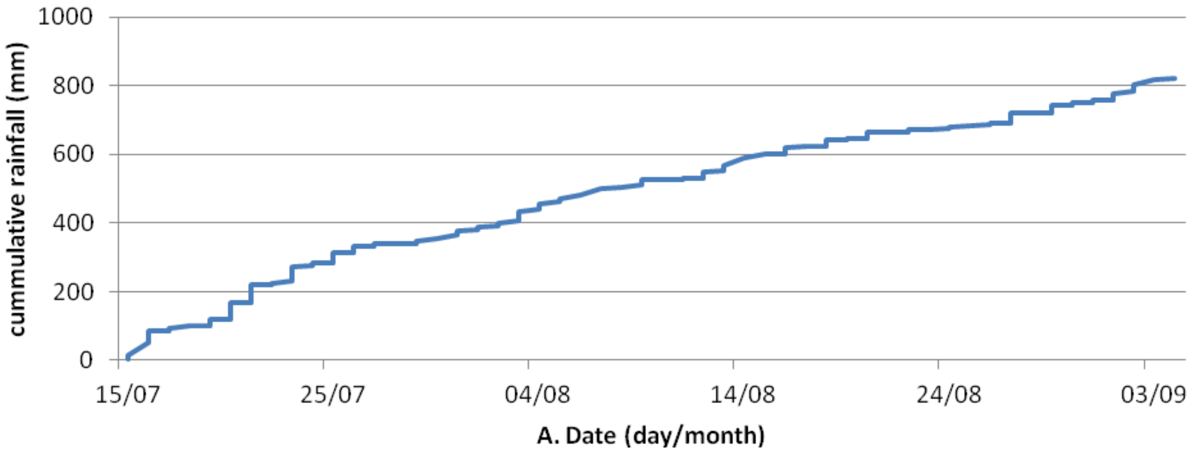


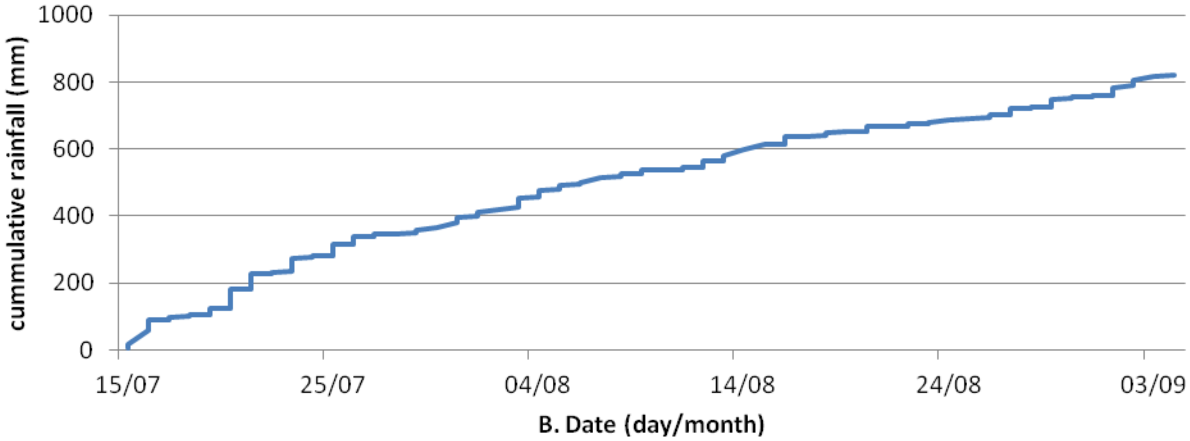
Annex 4. Rainfall data from July 15 to August 5 (2013) for rain gauges at Gedam and Tashmender (Wanzaye, Ethiopia).

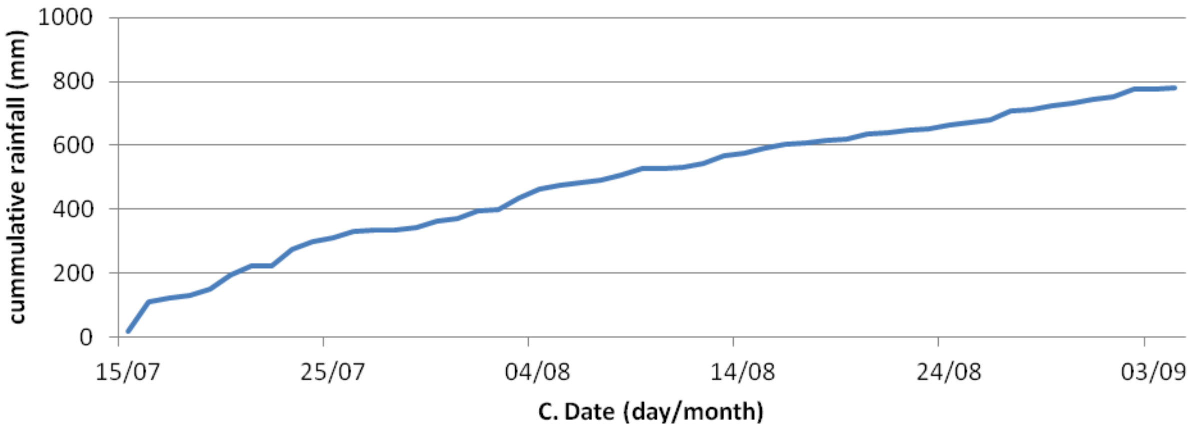
	GEDAM		TASHMENDER	
	7:00 (mm)	18:00 (mm)	7:00 (mm)	18:00 (mm)
JULY				
15	0.00	4.09	0.00	3.79
16	10.60	36.66	13.33	40.30
17	34.69	1.21	31.66	1.21
18	6.06	6.67	6.06	6.82
19	0.00	0.00	0.76	0.00
20	20.15	0.00	19.09	0.00
21	48.48	0.00	58.93	0.00
22	53.17	0.00	46.96	0.00
23	1.51	8.48	1.51	6.06
24	41.36	3.48	36.51	2.88
25	6.06	0.00	6.21	0.00
26	31.51	1.06	35.14	0.00
27	17.42	0.00	20.00	0.00
28	5.60	0.00	10.60	0.00
29	0.00	0.00	0.00	2.58
30	7.73	8.18	5.91	7.42
31	0.00	11.51	0.00	16.06
AUGUST				
1	11.66	2.42	14.85	6.82
2	7.57	6.06	11.66	5.76
3	4.54	7.57	0.61	6.06
4	27.57	6.97	28.63	3.03
5	16.66	5.00	19.54	4.70
6	9.24	9.09	8.48	4.09
7	3.03	15.15	3.79	15.15
8	0.00	6.36	0.00	6.82
9	0.00	6.21	4.70	0.00
10	13.63	0.00	13.18	0.00
11	0.00	0.00	0.00	0.00
12	6.06	0.00	5.91	0.00
13	19.69	1.51	19.39	3.03
14	16.81	22.12	13.33	19.69
15	0.00	11.51	0.00	13.18
16	0.00	0.00	0.00	0.00
17	18.18	1.67	24.24	1.51
18	1.51	0.00	0.00	1.67
19	20.15	0.00	10.76	0.61

20	2.58	0.00	1.51	0.00
21	16.97	0.00	15.00	0.61
22	0.00	2.27	0.00	1.06
23	5.45	0.00	6.06	0.00
24	1.51	4.70	2.88	6.82
25	1.97	2.73	3.03	2.88
26	0.00	4.24	0.00	4.24
27	3.94	0.00	5.30	0.00
28	28.78	0.00	20.91	0.00
29	3.03	0.00	2.27	0.00
30	19.69	2.12	25.00	1.67
31	5.76	0.00	4.09	0.00
SEPTEMBER				
1	9.54	0.00	6.06	0.00
2	18.18	7.27	20.60	8.48
3	19.69	12.12	15.00	12.12
4	0.00	4.40	0.00	2.80
5	1.00		1.20	

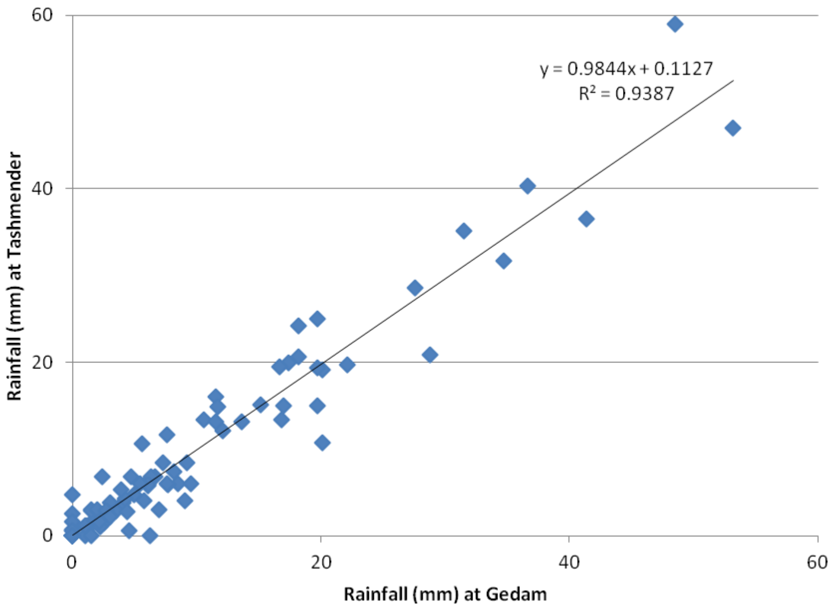
Annex 5.1 Cumulative rain curves for Gedam (A), Tashmender (B) and Wanzaye (C) (Ethiopia, 2013).







Annex 5.2 Relation between rainfall depth at Gedam and Tashmender (Wanzaye, Ethiopia, 2013).



Annex 5.3 Pearson correlation coefficients (at 1% significance level) for rainfall depth measured in Gedam, Tashmender and Wanzaye (output in SPSS).

Correlations

		Gedam	Tashmender	Wanzaye
Gedam	Pearson Correlation	1	,966**	,849**
	Sig. (2-tailed)		,000	,000
	N	52	52	52
Tashmender	Pearson Correlation	,966**	1	,835**
	Sig. (2-tailed)	,000		,000
	N	52	52	52
Wanzaye	Pearson Correlation	,849**	,835**	1
	Sig. (2-tailed)	,000	,000	
	N	52	52	52

**. Correlation is significant at the 0.01 level (2-tailed).

Annex 6. Fraction of the catchments' area for different crops. The surface area (ha) that a crop holds in the catchment is given under 'ha'. The fraction of the crop's area to the total catchment's area is given under '%'.

	barley		green pepper & onion		maize		millet		telba		tef		grassland	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
catchment 1	0	0	0	0	0	0	0	0	0.52	26.8	1.42	73.2	0	0
catchment 2	0	0	0	0	0	0	0.02	100.0	0	0	0	0	0	0
catchment 3	0.54	12.8	0.04	0.8	0.17	3.9	2.42	57.4	0	0	0.98	23.2	0	0
catchment 4	0.18	5.2	0.05	1.3	0	0	1.99	56.7	0.14	4.0	0.98	27.8	0.17	4.9
catchment 5	0	0	0.2	11.47	0	0	0.68	41.5	0	0	0.76	46.2	0	0
catchment 6	0.27	18.5	0	0	0	0	1.11	77.3	0	0	0.04	2.7	0	0
catchment 7	0	0	0	0	0	0	0	0	0	0	0.73	100.0	0	0
catchment 8	0	0	0	0	0.04	10.0	0.19	46.6	0	0	0.14	34.7	0.03	8.5
catchment 9	0.09	15.1	0.01	1.3	0	0	0.27	47.2	0	0	0.12	20.5	0.09	15.6
catchment 10	0.27	100.0	0	0	0	0	0	0	0	0	0	0	0	0
mean fraction (%)		15.2		1.5		1.4		42.7		3.1		32.8		2.9

Annex 7. Average soil depth (m) and average stoniness (%) for the 10 study areas (Wanzaye, Ethiopia, 2013).

catchment	number of observations soil depth	average soil depth (m)	number of observations stoniness	average stoniness (%)
1	5	0.23	5	95.4
2	4	0.44	4	77
3	4	0.77	5	53.4
4	5	0.39	4	65
5	5	0.31	4	62
6	5	0.61	4	17
7	2	0.66	3	28.3
8	4	0.17	4	89.8
9	3	0.42	3	80
10	2	0.17	2	99
min		0.17		17
max		0.77		99
mean		0.42		66.7
STDV		0.20		26.1

Annex 8.1 Gravimetric soil moisture content on dry weight basis for ten catchments in Wanzaye (Ethiopia) on July 19, August 12 and September 5 (2013).

Gravimetric soil moisture content (m³/m³)					
catchment CODE	19-Jul	12-Aug	05-Sep	average	catchment average
CA1L	0.309	0.274	0.243	0.275	0.327
CA1B	0.336	0.403	0.394	0.378	
CA2L	0.377	0.347	0.352	0.359	0.359
CA2B	0.338	0.407	0.335	0.360	
CA3L	0.343	0.389	0.369	0.367	0.396
CA3B	0.572	0.348	0.352	0.424	
CA4L	0.233	0.351	0.357	0.314	0.340
CA4B	0.394	0.343	0.364	0.367	
CA5L	0.132	0.289	0.226	0.216	0.293
CA5B	0.345	0.380	0.383	0.369	
CA6L	0.388	0.308	0.331	0.342	0.340
CA6B	0.323	0.351	0.341	0.338	
CA7L	0.341	0.361	0.325	0.342	0.292
CA7B	0.240	0.295	0.192	0.242	
CA8L	0.348	0.301	0.431	0.360	0.396
CA8B	0.398	0.453	0.444	0.432	
CA9L	0.353	0.429	0.421	0.401	0.385

CA9B	0.375	0.390	0.344	0.370	
CA10L	0.280	0.364	0.167	0.270	0.269
CA10B	0.249	0.256	0.297	0.267	
Mean	0.334	0.352	0.333		
STDEV	0.084	0.051	0.073		

Annex 8.2 Rainfall depth prior to soil sampling on July 19, August 12 and September 5 (Wanzaye, Ethiopia, 2013).

Total rain…	19-Jul	12-Aug	05-Sep
GEDAM [catchment 1-5]			
4 days before sampling (mm)	99.98	32.27	62.66
2 days before sampling (mm)	13.94	6.06	17.52
the night before sampling (mm)	0.00	6.06	1.00
TASHMENDER [catchment 5-10]			
4 days before sampling (mm)	103.92	30.60	60.20
2 days before sampling (mm)	14.85	5.91	16.12
the night before sampling (mm)	0.76	5.91	1.20

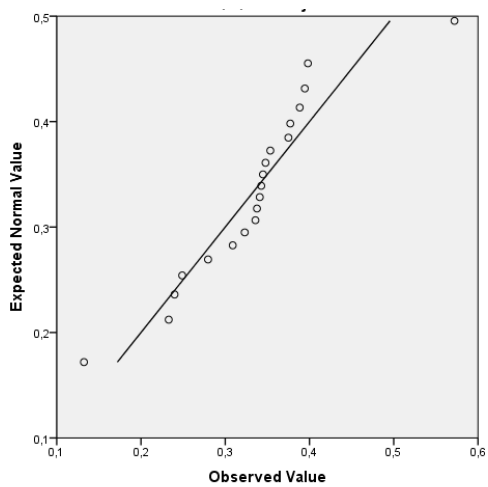
Annex 9.1 Check assumption of equal variance of the three data groups (July 19, August 12, September 5) for gravimetric soil moisture content by Levene's test, to perform a Repeated Measures ANOVA test (output in SPSS).

Test of Homogeneity of Variances

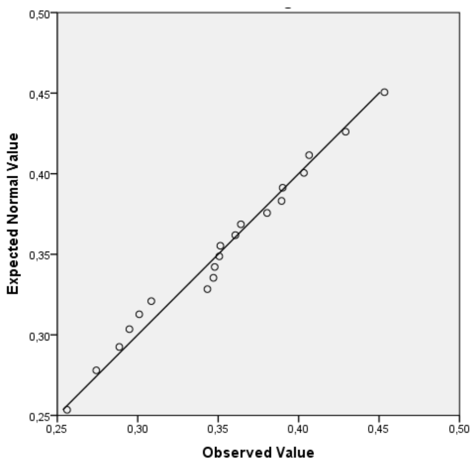
Moisture

Levene Statistic	df1	df2	Sig.
,620	2	57	,542

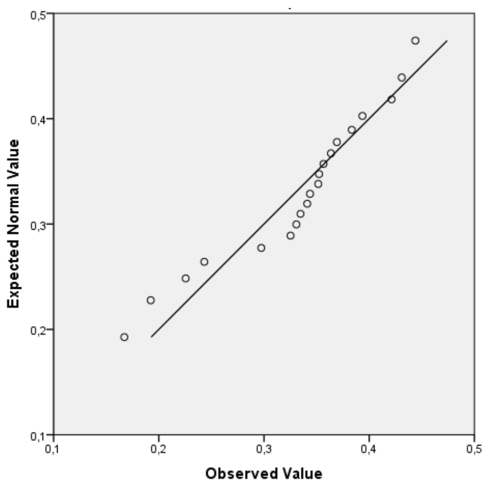
Annex 9.2 Check assumption of normal distribution of gravimetric soil moisture content to perform a Repeated Measures ANOVA test (output in SPSS).



Normal QQ plot of gravimetric moisture content July 19



Normal QQ plot of gravimetric moisture content August 12



Normal QQ plot of gravimetric moisture content September 5

Annex 9.3 Check assumption of covariances between successive groups (July 19, August 12, September 5) of gravimetric soil moisture content to perform a Repeated Measures ANOVA test (output in SPSS).

Correlations

		July	September	August
July	Pearson Correlation	1	,527*	,385
	Sig. (2-tailed)		,017	,093
	Sum of Squares and Cross-products	,142	,065	,033
	Covariance	,007	,003	,002
	N	20	20	20
September	Pearson Correlation	,527*	1	,560*
	Sig. (2-tailed)	,017		,010
	Sum of Squares and Cross-products	,065	,108	,042
	Covariance	,003	,006	,002
	N	20	20	20
August	Pearson Correlation	,385	,560*	1
	Sig. (2-tailed)	,093	,010	
	Sum of Squares and Cross-products	,033	,042	,053
	Covariance	,002	,002	,003
	N	20	20	20

*. Correlation is significant at the 0.05 level (2-tailed).

Annex 10. Changes in bulk density over time (July 19, August 12 and September 5, 2013) for ten catchments (two samples each) in Wanzaye, Ethiopia.

catchment code	bulk density (g/cm^3) July	bulk density (g/cm^3) August	bulk density (g/cm^3) September
CA1L	1.25	1.51	1.61
CA1B	1.79	1.71	1.74
CA2L	1.15	1.48	1.31
CA2B	1.55	1.51	1.68
CA3L	1.67	1.57	1.65
CA3B	1.69	1.55	1.73
CA4L	1.54	1.50	1.66
CA4B	1.26	1.80	1.65
CA5L	1.46	1.63	1.63
CA5B	1.56	1.76	1.75
CA6L	1.81	1.40	1.71
CA6B	1.52	1.43	1.44
CA7L	1.75	1.66	1.63

CA7B	1.84	1.63	1.40
CA8L	1.40	1.41	1.30
CA8B	1.48	1.64	1.48
CA9L	1.46	1.62	1.40
CA9B	1.60	1.68	1.51
CA10L	1.35	1.33	1.71
CA10B	1.48	1.55	1.51
mean	1.53	1.57	1.58
STDEV	0.19	0.12	0.14

Annex 11. Average *feses*' top width (m) and depth (m), right after establishment for the 10 study areas. Observations took place at the monitor sites (Annex 1). Average *feses* volume per ha was calculated by multiplying the average top width, average depth and *feses* density from Table 2.

catchment	number of observations	average top width *feses* (m)	average depth *feses* (m)	average *feses* volume/ha (m^3/ha)
1	6	0.31	0.08	5.18
2	/	/	/	/
3	6	0.17	0.12	5.03
4	3	0.31	0.14	2.31
5	6	0.36	0.14	21.05
6	6	0.20	0.10	8.13
7	4	0.20	0.10	1.55
8	3	0.20	0.12	10.35
9	3	0.44	0.14	11.61
10	4	0.25	0.11	14.03
min		0.17	0.08	1.55
max		0.44	0.14	21.05
mean		0.27	0.12	8.80
STDV		0.09	0.02	6.23

Annex 12. Monitor sites 3 (upper) and 4 (lower) in catchment 3 for three time records: July 27, August 9, and September 1 (Wanzaye, Ethiopia, 2013).

Annex 13. Classification for all monitor sites at the end of the rainy season (September 1), differentiating for: *feses* which got sedimented, *feses* which had been eroded deeper, and *feses* for which the development was not clearly visible.

CATCHMENT 1		CATCHMENT 3		CATCHMENT 4	
monitor site	class	monitor site	class	monitor site	class
1	unclear	1	eroded	1	unclear
2	eroded	2	sedimented	2	sedimented
3	sedimented	3	sedimented	3	sedimented
4	eroded	4	eroded	dominant trend	sedimented
5	eroded	5	eroded		
6	eroded	6	unclear		
dominant trend	eroded	dominant trend	eroded		

CATCHMENT 5		CATCHMENT 6		CATCHMENT 7	
monitor site	class	monitor site	class	monitor site	class
1	eroded	1	sedimented	1	eroded
2	eroded	2	sedimented	2	eroded
3	sedimented	2b	sedimented	3	sedimented
4	eroded	3	eroded	dominant trend	eroded
5	sedimented	4	unclear		
6	sedimented	5	sedimented		
dominant trend	/	dominant trend	sedimented		

CATCHMENT 8		CATCHMENT 9		CATCHMENT 10	
monitor site	class	monitor site	class	monitor site	class
1	sedimented	1	eroded	1	unclear
2	sedimented	2	eroded	2	sedimented
3	sedimented	3	sedimented	3	eroded
dominant trend	sedimented	dominant trend	eroded	4	eroded
				dominant trend	eroded

Annex 14.1 Local surface slope (α, °), angle of the *feses* to the contour (β, °), and the corresponding calculated *feses* gradient (m/m). Each line represents a different *feses*. Catchment 2 does not comprise *feses*.

catchment	α (°)	β (°)	*feses* gradient (m/m)
1	7.58	90	0.133
	7.58	45	0.094
	8.97	80	0.155
	20.39	45	0.254
	20.39	40	0.230
	20.39	0	0.000
	12.21	45	0.151
	12.21	37	0.128
	19.73	45	0.246
	20.39	39	0.225
	20.39	65	0.333
	20.39	90	0.372
	14.81	40	0.167
min			0.000
max			0.372
mean			0.191
STDEV			0.100
3	3.48	20	0.021
	6.85	73	0.115
	3.34	48	0.043
	5.37	48	0.070
	5.37	85	0.094
	5.37	85	0.094
	1.00	4	0.001
	4.63	27	0.037
	6.73	0	0.000
	4.64	58	0.069
	6.03	35	0.060
	6.03	23	0.041
	2.85	60	0.043
	4.47	20	0.027
	4.47	30	0.039
	3.59	85	0.062
min			0.000
max			0.115
mean			0.051
STDEV			0.032
4	11.53	90	0.204
	9.34	90	0.164

	11.27	45	0.140
	8.90	84	0.156
	8.90	90	0.157
	11.49	25	0.084
	7.35	60	0.111
	4.12	5	0.006
	2.11	90	0.037
	0.75	60	0.011
	0.00	60	0.000
	2.11	5	0.003
	1.38	0	0.000
	1.38	90	0.024
min			0.000
max			0.204
mean			0.078
STDEV			0.075
5	3.3	45	0.041
	3.3	85	0.057
	2.69	55	0.038
	2.69	4	0.003
	2.69	0	0.000
	2.69	25	0.020
	3.9	40	0.044
	3.3	90	0.058
	3.9	45	0.048
	3.9	90	0.068
	3.3	0	0.000
	3.3	45	0.041
	3.3	10	0.010
	3.3	0	0.000
	2.36	85	0.041
	2.36	90	0.041
	3.89	85	0.068
min			0.000
max			0.068
mean			0.034
STDEV			0.024
6	3.43	45	0.042
	6.42	40	0.072
	1.7	40	0.019
	3.3	43	0.039
	3.3	43	0.039
	1.2	5	0.002
	2.11	0	0.000

	3.33	45	0.041
	2.11	45	0.026
	3.73	40	0.042
	2.87	30	0.025
	2.36	45	0.029
	3.3	78	0.056
	3.15	45	0.039
min			0.000
max			0.072
mean			0.034
STDEV			0.019
7	0.94	45	0.012
	0.94	45	0.012
min			0.012
max			0.012
mean			0.012
STDEV			0.000
8	5.75	77	0.098
	5.37	8	0.013
	11.46	0	0.000
	5.37	17	0.027
	2.67	40	0.030
	2.37	25	0.017
min			0.000
max			0.098
mean			0.031
STDEV			0.035
9	3.00	3	0.003
	3.00	25	0.022
	1.05	90	0.018
	3.90	90	0.068
min			0.003
max			0.068
mean			0.028
STDEV			0.028
10	3.3	30	0.029
	3.3	40	0.037
	3.3	17	0.017
	3.3	40	0.037
	3.3	80	0.057
min			0.017
max			0.057
mean			0.035
STDEV			0.015

Annex 14.2 Average *feses* gradient (m/m) and average angle between *feses* and contour line (°). Catchment 2 does not comprise *feses*.

catchment	number of observations	Average angle with contour (°)	average *feses* gradient (m/m)
1	13	48.3	0.191
2	/	/	/
3	16	43.8	0.051
4	14	56.7	0.078
5	18	48.8	0.034
6	16	38.4	0.034
7	2	45.0	0.012
8	8	31.1	0.031
9	4	52.0	0.028
10	5	41.4	0.035
min		31.1	0.012
max		56.7	0.191
mean		44.7	0.055
STDV		7.2	0.054

Annex 15.1 Outcome of multiple regression analysis for *feses* density by a stepwise procedure. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	SB_density	.	Stepwise (Criteria: Probability-of-F-to-enter <= ,050, Probability-of-F-to-remove >= ,100).

a. Dependent Variable: *feses*_density

Annex 15.2 Outcome of multiple regression analysis for *feses* density by a stepwise procedure. Output in SPSS for the coefficients of the excluded variables in model 1 with its significance.

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics Tolerance
1	tef	.008[b]	.028	.979	.011	.861
	silt_clay	.124[b]	.470	.652	.175	.964
	slope	.259[b]	1.048	.330	.368	.971

a. Dependent Variable: *feses*_density

b. Predictors in the Model: (Constant), SB_density

Annex 15.3 Outcome of multiple regression analysis for *feses* density by a stepwise procedure. Output in SPSS for the coefficients of model 1 with its significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	408,513	66,997		6,097	,000		
	SB_density	-,558	,189	-,721	-2,944	,019	1,000	1,000

a. Dependent Variable: *feses*_density

Annex 15.4 Outcome of multiple regression analysis for *feses* density by a stepwise procedure. Output in SPSS for the coefficient of determination of model 1.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,721[a]	,520	,460	131,71307

a. Predictors: (Constant), SB_density

b. Dependent Variable: *feses*_density

Annex 15.5 Outcome of multiple regression analysis for *feses* density by a stepwise procedure. Output in SPSS for the coefficients of the excluded variables in model 2 with its significance.

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
2	silt_clay	.124[b]	.470	.652	.175	.964
	barley	.251[b]	.899	.398	.322	.786
	millet	-.286[b]	-1.196	.271	-.412	.997
	soil_depth	-.431[b]	-2.097	.074	-.621	.998

a. Dependent Variable: *feses*_density

b. Predictors in the Model: (Constant), SB_density

Annex 16. *Feses* constructed perpendicularly to the contour line, which has eroded down to the bedrock. This photo is located at monitor site 2 in catchment 5 (Annex 1) (Wanzaye, Ethiopia, September 2013).

Annex 17. Data of the discharge measurements for catchment 1, 3 and 4: depth of flow h (m), area of the cross section A (m²), velocity V (m/s) and the measured discharge Q (m³/s). Also the slope gradient at the outlet S (m/m), wetted perimeter P (m) and hydraulic radius R (m) are presented for each flow depth to calculate Manning's roughness coefficient (n) based on eq. 13.

CATCHMENT 1 (S= 0.16 m/m)						
depth of flow h (m)	area A (m²)	velocity V (m/s)	discharge Q (m³/s)	wetted perimeter P (m)	hydraulic radius R (m)	Manning's roughness coefficient n
0.040	0.029	0.450	0.013	0.855	0.034	0.092
0.050	0.037	0.458	0.017	0.918	0.041	0.103
0.060	0.046	0.461	0.021	0.982	0.047	0.113
0.080	0.067	0.477	0.032	1.109	0.061	0.129
0.100	0.089	0.604	0.054	1.237	0.072	0.114
0.120	0.114	0.681	0.078	1.364	0.084	0.112

mean	0.110
STDEV	0.011

CATCHMENT 3 (S= 0.12 m/m)						
depth of flow h (m)	area A (m²)	velocity V (m/s)	discharge Q (m³/s)	wetted perimeter P (m)	hydraulic radius R (m)	Manning's roughness coefficient n
0.080	0.007	0.348	0.002	0.343	0.020	0.074
0.110	0.017	0.371	0.006	0.462	0.037	0.104
0.140	0.033	0.374	0.012	0.582	0.056	0.138
0.170	0.044	0.392	0.017	0.701	0.063	0.142
0.200	0.061	0.402	0.024	0.820	0.074	0.154
0.210	0.067	0.492	0.033	0.859	0.078	0.130
0.250	0.091	0.551	0.050	1.019	0.090	0.127
0.290	0.129	0.639	0.083	1.180	0.110	0.126
0.330	0.164	0.757	0.124	1.236	0.133	0.120

mean	0.124
STDEV	0.022

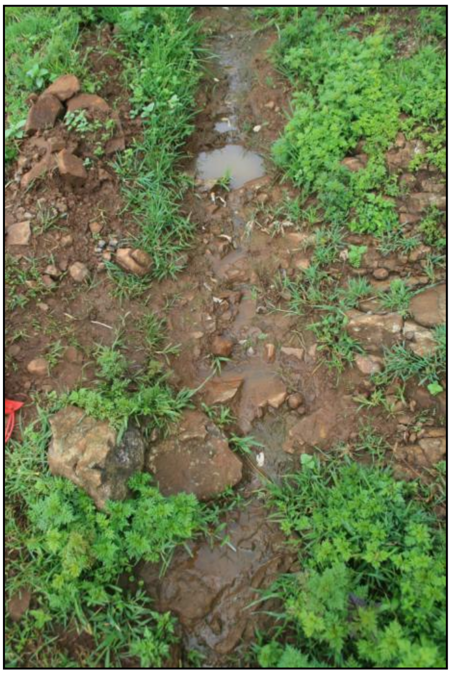
CATCHMENT 4 (S= 0.02 m/m)						
depth of flow h (m)	area A (m²)	velocity V (m/s)	discharge Q (m³/s)	wetted perimeter P (m)	hydraulic radius R (m)	Manning's roughness coefficient n
0.400	0.090	1.430	0.129	1.170	0.077	0.017
0.370	0.079	1.399	0.110	1.110	0.071	0.016
0.340	0.068	1.391	0.094	1.050	0.065	0.015

0.330	0.064	1.198	0.077	1.030	0.062	0.017	
0.300	0.053	1.150	0.061	0.970	0.055	0.017	
0.280	0.048	0.896	0.043	0.730	0.065	0.024	
0.260	0.044	0.826	0.036	0.690	0.064	0.026	
0.250	0.043	0.721	0.031	0.670	0.063	0.029	
0.215	0.037	0.712	0.027	0.600	0.062	0.029	
0.190	0.032	0.619	0.020	0.550	0.059	0.032	
0.170	0.029	0.441	0.013	0.510	0.057	0.044	
0.160	0.027	0.432	0.012	0.490	0.056	0.044	
0.150	0.026	0.275	0.007	0.470	0.054	0.069	
0.140	0.024	0.277	0.007	0.450	0.053	0.067	
						mean	0.032
						STDEV	0.017

Annex 18.1 Photographs used for the evaluation of the parameters for Manning's roughness coefficient after Cowan (1956) and the resulting Manning's roughness coefficient n.

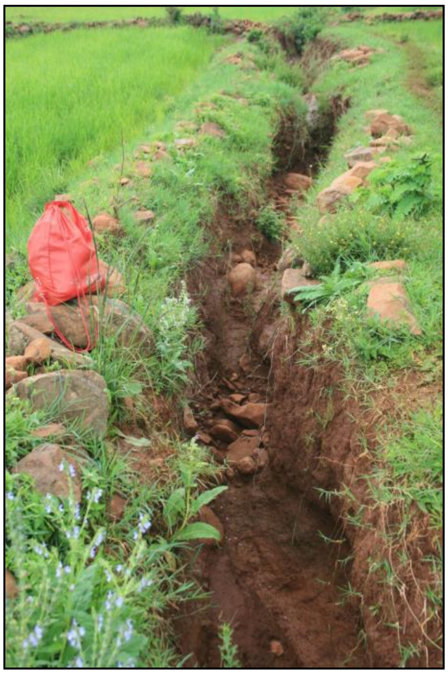
CATCHMENT 1. n= 0.083

CATCHMENT 2. n= 0.089



CATCHMENT 3. n= 0.054

CATCHMENT 4. n= 0.060



CATCHMENT 5. n= 0.067

CARCHMENT 6. n= 0.045

CATCHMENT 7. n= 0.050

CATCHMENT 8. n= 0.123

CATCHMENT 9. n= 0.043

CATCHMENT 10. n= 0.071


Annex 18.2 Evaluation of the parameters for Manning's roughness coefficient after Cowan (1956) by 8 geomorphologists.

	Roughness values CATCHMENT 1					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.070	0.020	0.005	0.015	0.010	1.150
	0.020	0.010	0.005	0.025	0.001	1.150
	0.030	0.010	0.005	0.010	0.000	1.000
	0.020	0.005	0.005	0.030	0.002	1.000
	0.040	0.020	0.010	0.020	0.010	1.150
	0.025	0.010	0.003	0.000	0.002	1.000
	0.040	0.010	0.005	0.020	0.000	1.150
	0.050	0.012	0.011	0.015	0.005	1.150
mean	0.037	0.012	0.006	0.017	0.004	1.094
STDEV	0.017	0.005	0.003	0.009	0.004	0.078

Roughness values CATCHMENT 2					
n_0	n_1	n_2	n_3	n_4	n_5
0.040	0.005	0.005	0.020	0.010	1.150
0.220	0.005	0.005	0.002	0.010	1.000
0.028	0.010	0.005	0.000	0.005	1.000
0.030	0.005	0.005	0.020	0.005	1.000
0.030	0.020	0.005	0.020	0.005	1.150

	0.022	0.010	0.002	0.020	0.005	1.000
	0.024	0.010	0.005	0.014	0.010	1.150
	0.028	0.005	0.000	0.013	0.006	1.000
	0.025	0.005	0.000	0.015	0.005	1.300
mean	0.050	0.008	0.004	0.014	0.007	1.083
STDEV	0.060	0.005	0.002	0.007	0.002	0.103

	Roughness values CATCHMENT 3					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.025	0.020	0.005	0.000	0.010	1.150
	0.025	0.005	0.002	0.002	0.001	1.000
	0.024	0.005	0.000	0.000	0.100	1.000
	0.025	0.004	0.002	0.000	0.000	1.000
	0.025	0.010	0.005	0.020	0.005	1.000
	0.025	0.002	0.001	0.000	0.000	1.000
	0.025	0.005	0.000	0.000	0.005	1.150
	0.025	0.001	0.000	0.001	0.010	1.000
mean	0.025	0.007	0.002	0.003	0.016	1.038
STDEV	0.000	0.006	0.002	0.007	0.034	0.069

	Roughness values CATCHMENT 4					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.020	0.020	0.015	0.020	0.000	1.300
	0.028	0.005	0.005	0.010	0.000	1.000
	0.028	0.005	0.000	0.000	0.000	1.000
	0.020	0.010	0.000	0.015	0.000	1.000
	0.020	0.020	0.010	0.020	0.010	1.000
	0.020	0.010	0.004	0.025	0.000	1.000
	0.030	0.020	0.000	0.010	0.010	1.150
	0.020	0.010	0.002	0.013	0.001	1.000
mean	0.023	0.013	0.005	0.014	0.003	1.056
STDEV	0.005	0.007	0.005	0.008	0.005	0.112

	Roughness values CATCHMENT 5					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.025	0.015	0.015	0.010	0.000	1.300
	0.020	0.005	0.005	0.010	0.000	1.150
	0.030	0.010	0.005	0.000	0.000	1.000
	0.020	0.017	0.003	0.005	0.000	1.000
	0.040	0.010	0.010	0.020	0.010	1.150
	0.020	0.012	0.010	0.020	0.000	1.150
	0.030	0.020	0.005	0.010	0.010	1.130
	0.020	0.015	0.012	0.013	0.001	1.000
mean	0.026	0.013	0.008	0.011	0.003	1.110

STDEV	0.007	0.005	0.004	0.007	0.005	0.105

	Roughness values CATCHMENT 6					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.050	0.020	0.015	0.010	0.000	1.150
	0.021	0.000	0.000	0.002	0.000	1.000
	0.020	0.005	0.000	0.000	0.000	1.150
	0.020	0.020	0.000	0.010	0.001	1.000
	0.020	0.005	0.005	0.010	0.005	1.000
	0.020	0.000	0.000	0.020	0.001	1.000
	0.024	0.005	0.000	0.000	0.000	1.000
	0.020	0.010	0.004	0.000	0.001	1.000
mean	0.024	0.008	0.003	0.007	0.001	1.038
STDEV	0.010	0.008	0.005	0.007	0.002	0.069

	Roughness values CATCHMENT 7					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.020	0.010	0.015	0.000	0.010	1.150
	0.020	0.010	0.010	0.000	0.000	1.000
	0.020	0.000	0.005	0.000	0.000	1.000
	0.020	0.020	0.001	0.000	0.000	1.000
	0.020	0.010	0.010	0.100	0.005	1.000
	0.020	0.006	0.005	0.000	0.000	1.000
	0.020	0.005	0.000	0.000	0.000	1.000
	0.020	0.000	0.005	0.000	0.002	1.000
mean	0.020	0.008	0.006	0.013	0.002	1.019
STDEV	0.000	0.007	0.005	0.035	0.004	0.053

	Roughness values CATCHMENT 8					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.070	0.005	0.015	0.040	0.010	1.150
	0.028	0.010	0.005	0.020	0.008	1.150
	0.040	0.005	0.005	0.010	0.050	1.150
	0.050	0.001	0.000	0.050	0.010	1.000
	0.070	0.020	0.010	0.050	0.010	1.150
	0.030	0.010	0.010	0.020	0.010	1.000
	0.050	0.010	0.000	0.025	0.010	1.000
	0.050	0.005	0.006	0.060	0.010	1.150
mean	0.049	0.008	0.006	0.034	0.015	1.094
STDEV	0.016	0.006	0.005	0.018	0.014	0.078

	Roughness values CATCHMENT 9					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.050	0.020	0.015	0.015	0.000	0.150
	0.025	0.005	0.005	0.000	0.000	1.000
	0.028	0.005	0.005	0.010	0.005	1.150
	0.025	0.010	0.000	0.010	0.000	1.000
	0.025	0.010	0.005	0.040	0.005	1.150
	0.025	0.007	0.003	0.002	0.000	1.000
	0.024	0.010	0.000	0.000	0.005	1.000
	0.025	0.005	0.000	0.000	0.001	0.000
mean	0.028	0.009	0.004	0.010	0.002	0.806
STDEV	0.009	0.005	0.005	0.014	0.003	0.458

	Roughness values CATCHMENT 10					
	n_0	n_1	n_2	n_3	n_4	n_5
	0.070	0.010	0.010	0.030	0.010	1.000
	0.025	0.000	0.010	0.010	0.000	1.000
	0.028	0.005	0.005	0.000	0.005	1.000
	0.025	0.010	0.000	0.020	0.000	1.000
	0.025	0.020	0.020	0.050	0.005	1.150
	0.025	0.002	0.007	0.025	0.000	1.000
	0.030	0.010	0.005	0.010	0.010	1.000
	0.025	0.005	0.002	0.010	0.001	1.000
mean	0.032	0.008	0.007	0.019	0.004	1.019
STDEV	0.016	0.006	0.006	0.016	0.004	0.053

Annex 18.3 Coefficient of variation for the estimated parameters of Manning's roughness coefficient after Cowan (1956).

	coefficient of variation for roughness parameters					
	n_0	n_1	n_2	n_3	n_4	n_5
catchment 1	0.464	0.433	0.457	0.547	1.111	0.071
catchment 2	1.216	0.566	0.595	0.533	0.339	0.095
catchment 3	0.014	0.934	1.120	2.420	2.078	0.067
catchment 4	0.195	0.524	1.211	0.550	1.739	0.106
catchment 5	0.284	0.363	0.520	0.620	1.739	0.095
catchment 6	0.429	0.983	1.755	1.112	1.690	0.067
catchment 7	0.000	0.853	0.786	2.828	1.714	0.052
catchment 8	0.327	0.697	0.808	0.524	0.967	0.071
catchment 9	0.311	0.557	1.205	1.409	1.254	0.568
catchment 10	0.494	0.807	0.839	0.809	1.116	0.052
mean	0.373	0.672	0.930	1.135	1.375	0.124
STDEV	0.342	0.215	0.397	0.843	0.513	0.157

Annex 19.1 Discharge (Q) calculations for ten subcatchments (with slope gradient measured at the outlet S (m/m) and roughness coefficient n) in Wanzaye (Ethiopia) using the Gauckler-Manning formula (eq. 13) (Manning, 1891) comprising the following variables: depth of flow (h), area of the cross section (A), wetted perimeter(P) and hydraulic radius (R).

CATCHMENT 1 (S= 0.16 m/m; n= 0.083)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.040	0.029	0.855	0.034	0.014
0.050	0.037	0.918	0.041	0.021
0.060	0.046	0.982	0.047	0.029
0.080	0.067	1.109	0.061	0.050
0.100	0.089	1.237	0.072	0.075
0.120	0.114	1.364	0.084	0.105

CATCHMENT 2 (S= 0.12 m/m; n= 0.089)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.020	0.002	0.174	0.010	0.000
0.040	0.007	0.347	0.019	0.002
0.060	0.015	0.521	0.029	0.006
0.080	0.027	0.694	0.039	0.012
0.100	0.042	0.868	0.048	0.022
0.120	0.061	1.041	0.058	0.036
0.140	0.083	1.215	0.068	0.054
0.160	0.108	1.388	0.078	0.078

CATCHMENT 3 (S= 0.12 m/m, n= 0.054)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.080	0.007	0.343	0.020	0.003
0.110	0.017	0.462	0.037	0.012
0.140	0.033	0.582	0.056	0.031
0.170	0.044	0.701	0.063	0.045
0.200	0.061	0.820	0.074	0.069
0.210	0.067	0.859	0.078	0.079
0.250	0.091	1.019	0.090	0.118
0.290	0.129	1.180	0.110	0.191
0.330	0.164	1.236	0.133	0.275

CATCHMENT 4 (S= 0.02 m/m; n= 0.060)				
depth of flow h (m)	area A (m²)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m³/s)
0.400	0.090	1.170	0.077	0.007
0.370	0.079	1.110	0.071	0.008
0.340	0.068	1.050	0.065	0.009
0.330	0.064	1.030	0.062	0.009
0.300	0.053	0.970	0.055	0.011
0.280	0.048	0.730	0.065	0.013
0.260	0.044	0.690	0.064	0.015
0.250	0.043	0.670	0.063	0.016
0.215	0.037	0.600	0.062	0.017
0.190	0.032	0.550	0.059	0.017
0.170	0.029	0.510	0.057	0.022
0.160	0.027	0.490	0.056	0.024
0.150	0.026	0.470	0.054	0.030
0.140	0.024	0.450	0.053	0.036

CATCHMENT 5 (S= 0.02 m/m; n= 0.067)				
depth of flow h (m)	area A (m²)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m³/s)
0.030	0.017	0.607	0.027	0.003
0.040	0.022	0.633	0.036	0.005
0.050	0.028	0.658	0.043	0.007
0.065	0.038	0.697	0.054	0.011
0.080	0.047	0.735	0.065	0.015
0.115	0.071	0.823	0.086	0.027

CATCHMENT 6 (S= 0.02 m/m; n= 0.045)				
depth of flow h (m)	area A (m²)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m³/s)
0.080	0.080	1.093	0.073	0.002
0.100	0.103	1.157	0.089	0.004
0.140	0.151	1.221	0.123	0.006
0.200	0.230	1.250	0.184	0.005
0.260	0.318	1.347	0.236	0.011
0.350	0.460	1.539	0.299	0.022
0.060	0.059	1.715	0.034	0.036
0.110	0.114	1.946	0.059	0.061

CATCHMENT 7 (S= 0.02 m/m; n= 0.050)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.060	0.027	0.570	0.047	0.001
0.080	0.036	0.610	0.059	0.001
0.090	0.041	0.690	0.060	0.002
0.140	0.049	0.790	0.062	0.002
0.160	0.077	0.830	0.093	0.004
0.200	0.097	0.910	0.107	0.006

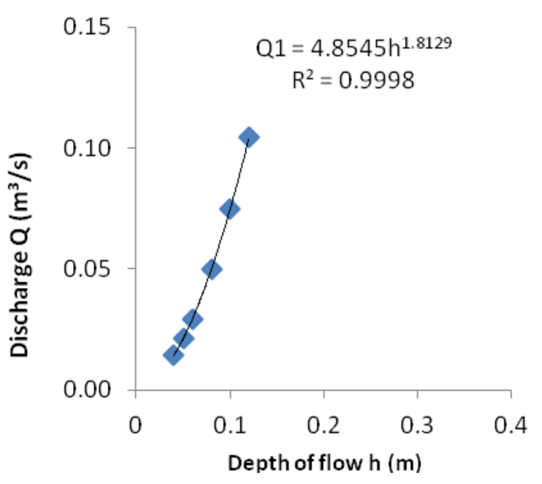
CATCHMENT 8 (S= 0.51 m/m; n= 0.123)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.06	0.06	1.12	0.0535714	0.021
0.08	0.08	1.16	0.0689655	0.032
0.1	0.1	1.2	0.0833333	0.046
0.13	0.13	1.26	0.1031746	0.069
0.17	0.17	1.34	0.1268657	0.103

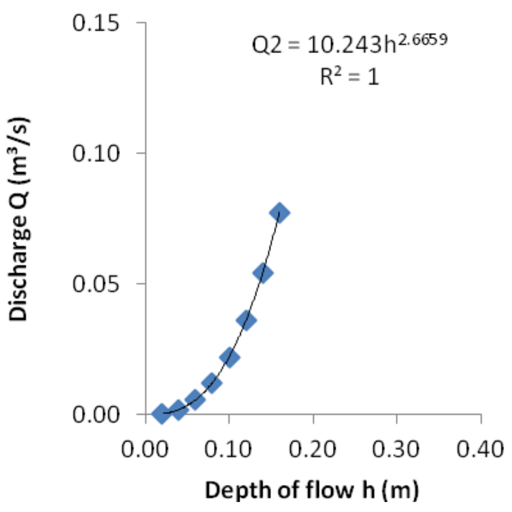
CATCHMENT 9 (S= 0.18 m/m; n= 0.043)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.060	0.024	0.520	0.046	0.001
0.120	0.048	0.640	0.075	0.003
0.190	0.076	0.780	0.097	0.005
0.200	0.080	0.800	0.100	0.005
0.230	0.092	0.860	0.107	0.006
0.290	0.116	0.980	0.118	0.009
0.360	0.144	1.120	0.129	0.011
0.410	0.164	1.220	0.134	0.013
0.460	0.184	1.320	0.139	0.015
0.480	0.192	1.360	0.141	0.016

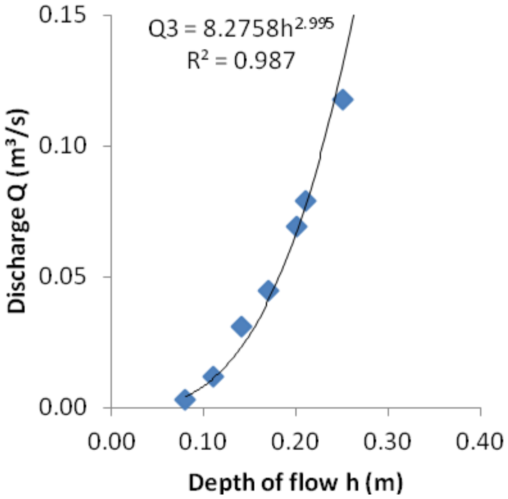
CATCHMENT 10 (S= 0.51 m/m; n= 0.071)				
depth of flow h (m)	area A (m^2)	wetted perimeter P (m)	hydraulic radius R (m)	calculated discharge Q (m^3/s)
0.045	0.015	0.430	0.036	0.010
0.050	0.017	0.440	0.039	0.011
0.058	0.020	0.455	0.043	0.014
0.075	0.026	0.490	0.052	0.021

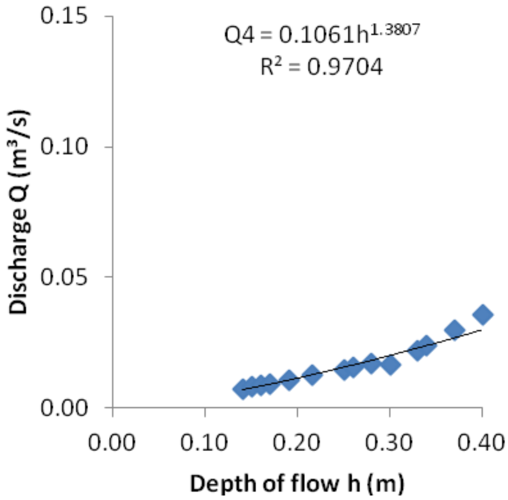
0.080	0.027	0.500	0.054	0.023
0.115	0.039	0.570	0.069	0.039
0.120	0.041	0.580	0.070	0.041
0.160	0.054	0.660	0.082	0.061
0.190	0.065	0.720	0.090	0.076
0.250	0.085	0.840	0.101	0.109
0.290	0.098	0.936	0.105	0.128
0.320	0.106	1.011	0.105	0.139
0.350	0.113	1.087	0.104	0.147
0.360	0.115	1.112	0.104	0.149
0.390	0.120	1.187	0.101	0.154

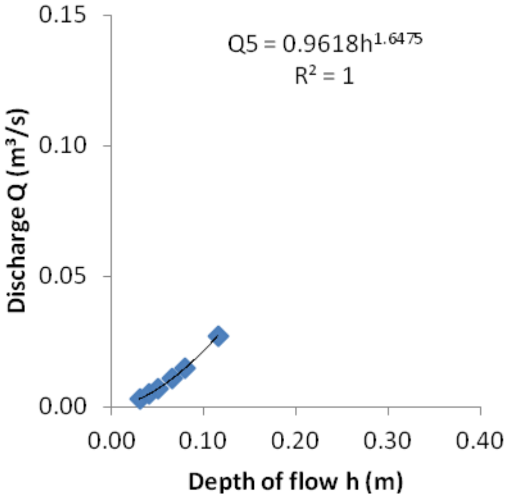
Annex 19.2 Rating curve for ten subcatchments in Wanzaye (Ethiopia) (Q1 for catchment 1 etc.).

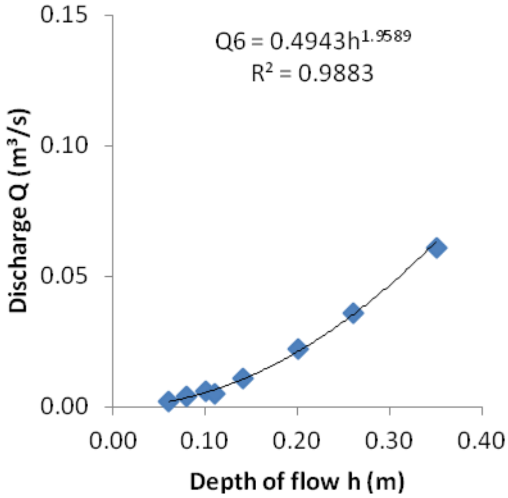


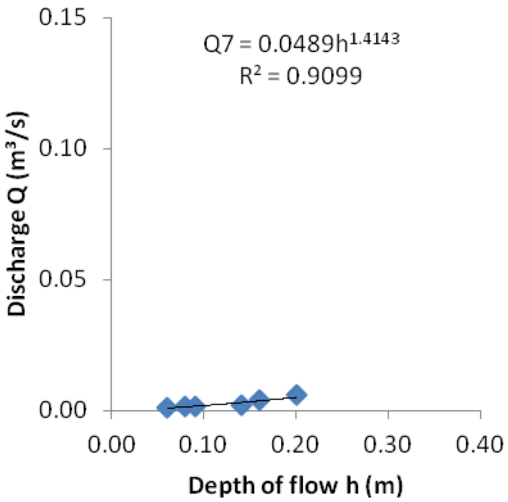


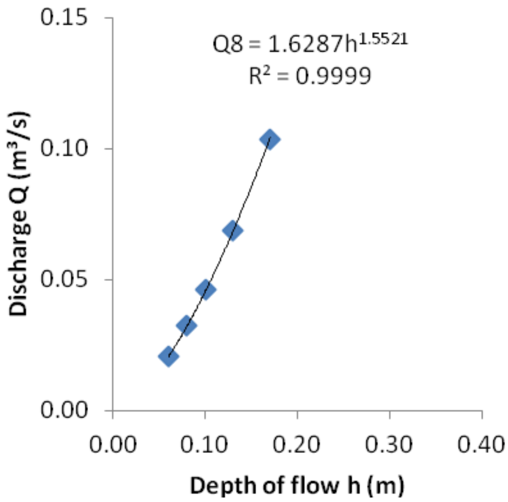

Q3 = 8.2758h^2.995
R² = 0.987
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)

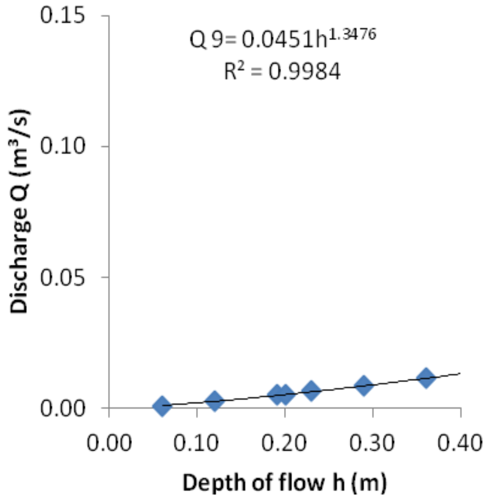

Q4 = 0.1061h^1.3807
R² = 0.9704
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)

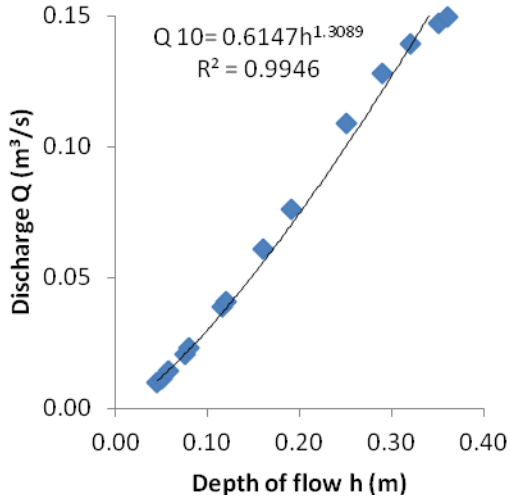

Q5 = 0.9618h^1.6475
R² = 1
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)


Q6 = 0.4943h^1.9589
R² = 0.9883
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)


Q7 = 0.0489h^1.4143
R² = 0.9099
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)


Q8 = 1.6287h^1.5521
R² = 0.9999
Discharge Q (m³/s)
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
Depth of flow h (m)





Annex 20. Calculated runoff and runoff coefficients for different runoff events in the study areas in Wanzaye (Ethiopia, 2013). The following rainfall variables are also presented: rainfall depth measured at the day of the runoff event, the night before the runoff event, 24 hours before the runoff event and 5 days before the runoff event.

date	calculated runoff (mm)	runoff coefficient (%)	rainfall fallen that day (mm)	half day antecedent rainfall (mm)	1 day antecedent rainfall (mm)	5 days antecedent rainfall (mm)
CATCHMENT 1						
16/7	27.19	74.16	36.66	10.60	14.69	/
18/7	0.04	0.53	6.67	6.06	7.27	/
23/7	0.26	3.08	8.48	1.51	1.51	129.97
24/7	0.98	28.13	3.48	41.36	49.84	173.15
30/7	2.94	35.99	8.18	7.73	7.73	63.32
31/7	1.08	9.37	11.51	0.00	8.18	39.99
4/8	3.51	50.44	6.97	27.57	35.14	87.10
5/8	0.37	7.33	5.00	16.66	23.63	102.56
7/8	7.54	49.78	15.15	3.03	12.12	95.74
8/8	1.66	26.15	6.36	0.00	15.15	100.28
15/8	1.08	9.38	11.51	0.00	22.12	66.20
22/8	0.59	25.84	2.27	0.00	0.00	42.87
25/8	0.40	14.72	2.73	1.97	6.67	32.87
30/8	0.16	7.58	2.12	19.69	19.69	62.41
2/9	5.21	71.65	7.27	18.18	18.18	58.32
3/9	5.71	47.13	12.12	19.69	26.96	82.26
CATCHMENT 2						
15/7	0.01	0.27	4.09	0.00	/	/
18/7	0.57	8.55	6.67	6.06	7.27	/
24/7	0.06	1.75	3.48	41.36	49.84	173.15
30/7	0.59	7.18	8.18	7.73	7.73	63.32

31/7	0.17	1.48	11.51	0.00	8.18	39.99
1/8	0.20	8.40	2.42	11.66	23.18	44.69
4/8	0.09	1.23	6.97	27.57	35.14	87.10
6/8	0.54	5.90	9.09	9.24	14.24	93.62
7/8	2.08	13.70	15.15	3.03	12.12	95.74
8/8	0.39	6.12	6.36	0.00	15.15	100.28
15/8	1.41	12.21	11.51	0.00	22.12	66.20
22/8	0.03	1.34	2.27	0.00	0.00	42.87
24/8	0.13	2.79	4.70	1.51	1.51	28.78
25/8	0.09	3.16	2.73	1.97	6.67	32.87
26/8	0.09	2.03	4.24	0.00	2.73	18.63
2/9	0.39	5.38	7.27	18.18	18.18	58.32
CATCHMENT 3						
16/7	25.61	69.86	36.66	10.60	14.69	/
18/7	1.40	20.94	6.67	6.06	7.27	/
23/7	1.45	17.11	8.48	1.51	1.51	129.97
24/7	0.49	14.15	3.48	41.36	49.84	173.15
30/7	6.02	73.63	8.18	7.73	7.73	63.32
5/8	1.84	36.81	5.00	16.66	23.63	102.56
6/8	4.47	49.13	9.09	9.24	14.24	93.62
7/8	6.29	41.55	15.15	3.03	12.12	95.74
14/8	5.51	24.92	22.12	16.81	18.33	63.93
15/8	5.97	51.89	11.51	0.00	22.12	66.20
22/8	0.36	15.85	2.27	0.00	0.00	42.87
24/8	3.42	72.83	4.70	1.51	1.51	28.78
25/8	0.44	16.05	2.73	1.97	6.67	32.87
CATCHMENT 4						
18/7	0.30	4.58	6.67	6.06	7.27	/
23/7	0.65	7.68	8.48	1.51	1.51	129.97
30/7	1.80	21.96	8.18	7.73	7.73	63.32
31/7	2.14	18.61	11.51	0.00	8.18	39.99
3/8	1.55	20.40	7.57	4.54	10.60	59.69
4/8	2.76	39.62	6.97	27.57	35.14	87.10
6/8	2.44	26.88	9.09	9.24	14.24	93.62
7/8	2.15	14.22	15.15	3.03	12.12	95.74
14/8	2.64	11.93	22.12	16.81	18.33	63.93
15/8	1.56	13.59	11.51	0.00	22.12	66.20
24/8	0.97	20.68	4.70	1.51	1.51	28.78
2/9	2.07	28.45	7.27	18.18	18.18	58.32
3/9	2.53	20.86	12.12	19.69	26.96	82.26
CATCHMENT 5						
18/7	0.75	11.32	6.67	6.06	7.27	/
23/7	2.65	31.23	8.48	1.51	1.51	129.97
24/7	0.34	9.70	3.48	41.36	49.84	173.15

31/7	5.28	45.83	11.51	0.00	8.18	39.99
3/8	0.45	5.88	7.57	4.54	10.60	59.69
4/8	2.92	41.93	6.97	27.57	35.14	87.10
5/8	0.87	17.31	5.00	16.66	23.63	102.56
6/8	1.98	21.81	9.09	9.24	14.24	93.62
7/8	5.30	34.98	15.15	3.03	12.12	95.74
8/8	2.80	44.00	6.36	0.00	15.15	100.28
9/8	0.51	8.16	6.21	0.00	6.36	71.50
14/8	13.91	62.89	22.12	16.81	18.33	63.93
15/8	2.99	25.97	11.51	0.00	22.12	66.20
22/8	0.36	15.88	2.27	0.00	0.00	42.87
24/8	1.01	21.47	4.70	1.51	1.51	28.78
25/8	0.26	9.42	2.73	1.97	6.67	32.87
26/8	0.46	10.73	4.24	0.00	2.73	18.63
CATCHMENT 6						
23/7	0.30	5.03	6.06	1.51	1.51	134.07
24/7	0.10	3.55	2.88	36.51	42.57	169.06
3/8	1.29	21.33	6.06	0.61	6.36	71.65
6/8	0.77	18.87	4.09	8.48	13.18	95.28
7/8	1.11	7.32	15.15	3.79	7.88	84.68
8/8	0.16	2.30	6.82	0.00	15.15	93.47
14/8	2.95	14.99	19.69	13.33	16.36	54.84
15/8	3.94	29.86	13.18	0.00	19.69	61.35
22/8	0.23	21.53	1.06	0.00	0.61	31.66
24/8	4.02	58.97	6.82	2.88	2.88	27.72
3/9	1.14	9.41	12.12	15.00	23.48	80.89
CATCHMENT 7						
23/7	1.18	19.44	6.06	1.51	1.51	134.07
24/7	0.45	15.57	2.88	36.51	42.57	169.06
30/7	2.12	28.56	7.42	5.91	8.48	74.23
1/8	0.64	9.42	6.82	14.85	30.90	57.41
3/8	0.43	7.06	6.06	0.61	6.36	71.65
4/8	0.29	9.44	3.03	28.63	34.69	97.86
6/8	0.41	9.93	4.09	8.48	13.18	95.28
7/8	0.41	2.73	15.15	3.79	7.88	84.68
8/8	0.34	5.04	6.82	0.00	15.15	93.47
14/8	0.78	3.95	19.69	13.33	16.36	54.84
15/8	3.73	28.30	13.18	0.00	19.69	61.35
3/9	1.48	12.24	12.12	15.00	23.48	80.89
CATCHMENT 8						
16/07	31.09	77.17	40.30	13.33	17.12	/
18/07	1.65	24.20	6.82	6.06	7.27	/
01/08	72.44	1062.69	6.82	14.85	30.90	57.41
03/08	136.66	2255.28	6.06	0.61	6.36	71.65

04/08	66.16	2183.86	3.03	28.63	34.69	97.86
06/08	28.09	686.76	4.09	8.48	13.18	95.28
07/08	21.32	140.74	15.15	3.79	7.88	84.68
08/08	8.49	124.54	6.82	0.00	15.15	93.47
14/08	50.80	257.96	19.69	13.33	16.36	54.84
15/08	65.22	494.87	13.18	0.00	19.69	61.35
18/08	8.52	511.32	1.67	0.00	1.51	74.99
02/09	64.90	765.10	8.48	20.60	20.60	59.69
03/09	68.08	561.74	12.12	15.00	23.48	80.89
CATCHMENT 9						
16/7	1.03	2.56	40.30	13.33	17.12	/
18/7	0.08	1.11	6.82	6.06	7.27	/
31/7	3.70	23.03	16.06	0.00	7.42	46.51
1/8	1.29	18.97	6.82	14.85	30.90	57.41
5/8	0.53	11.24	4.70	19.54	22.57	113.01
6/8	1.30	31.73	4.09	8.48	13.18	95.28
7/8	3.94	25.98	15.15	3.79	7.88	84.68
8/8	5.65	82.83	6.82	0.00	15.15	93.47
14/8	14.39	73.09	19.69	13.33	16.36	54.84
15/8	3.23	24.51	13.18	0.00	19.69	61.35
24/8	0.27	3.99	6.82	2.88	2.88	27.72
2/9	2.11	24.89	8.48	20.60	20.60	59.69
CATCHMENT 10						
16/7	281.13	697.68	40.30	13.33	17.12	/
18/7	8.75	128.42	6.82	6.06	7.27	/
24/7	7.98	277.25	2.88	36.51	42.57	169.06
30/7	93.57	1260.64	7.42	5.91	8.48	74.23
31/7	164.62	1025.21	16.06	0.00	7.42	46.51
6/8	13.62	333.08	4.09	8.48	13.18	95.28
7/8	7.46	49.26	15.15	3.79	7.88	84.68
14/8	58.49	297.00	19.69	13.33	16.36	54.84

Annex 21. Output in SPSS for Pearson correlation coefficients (PC) between the following catchment-averaged characteristics of the ten study areas in Wanzaye (Ethiopia, 2013): stone bund density (SBD), *feses* density (FD), fraction of cultivated barley, millet or tef, surface stoniness (stoniness), soil depth, top width of *feses* (top width), depth of *feses* (depth_f), catchment-averaged slope (slope, °), *feses* gradient (f_gradient), and runoff coefficient (RC) for the ten subcatchments in Wanzaye (Ethiopia, 2013). Note that data from the study areas 8 and 10 have been omitted (N=8).

Correlations

		SBD	FD	barley	millet	tef	stoniness	soil_depth	top_width	depth_f	slope	f_gradient	RC
SBD	PC	1	-,562	-,437	-,330	,285	,743*	-,637	,348	-,127	,352	,229	-,176
	Sig. (2-tailed)		,147	,279	,425	,494	,035	,089	,399	,764	,392	,585	,677
	N	8	8	8	8	8	8	8	8	8	8	8	8
FD	PC	-,562	1	,408	-,032	-,109	-,311	,005	,375	,451	-,097	,081	,475
	Sig. (2-tailed)	,147		,315	,941	,797	,453	,990	,360	,262	,819	,849	,235
	N	8	8	8	8	8	8	8	8	8	8	8	8
barley	PC	-,437	,408	1	,381	-,574	-,374	,476	,174	,364	-,359	-,197	,365
	Sig. (2-tailed)	,279	,315		,352	,137	,362	,233	,680	,376	,382	,640	,374
	N	8	8	8	8	8	8	8	8	8	8	8	8
millet	PC	-,330	-,032	,381	1	-,944**	-,094	,183	-,488	-,349	-,568	-,522	-,307
	Sig. (2-tailed)	,425	,941	,352		,000	,824	,664	,220	,396	,142	,185	,459
	N	8	8	8	8	8	8	8	8	8	8	8	8
tef	PC	,285	-,109	-,574	-,944**	1	-,021	-,099	,254	,178	,443	,345	,067
	Sig. (2-tailed)	,494	,797	,137	,000		,960	,816	,543	,672	,272	,403	,875
	N	8	8	8	8	8	8	8	8	8	8	8	8
stoniness	PC	,743*	-,311	-,374	-,094	-,021	1	-,726*	,257	-,167	,566	,512	,219
	Sig. (2-tailed)	,035	,453	,362	,824	,960		,041	,538	,692	,144	,195	,603
	N	8	8	8	8	8	8	8	8	8	8	8	8
soil_depth	PC	-,637	,005	,476	,183	-,099	-,726*	1	-,451	,033	-,518	-,517	,081
	Sig. (2-tailed)	,089	,990	,233	,664	,816	,041		,261	,938	,188	,189	,849

	N	8	8	8	8	8	8	8	8	8	8	8	8
top_width	PC	,348	,375	,174	-,488	,254	,257	-,451	1	,817*	,202	,337	,508
	Sig. (2-tailed)	,399	,360	,680	,220	,543	,538	,261		,013	,632	,414	,198
	N	8	8	8	8	8	8	8	8	8	8	8	8
depth_f	PC	-,127	,451	,364	-,349	,178	-,167	,033	,817*	1	-,097	,087	,607
	Sig. (2-tailed)	,764	,262	,376	,396	,672	,692	,938	,013		,820	,838	,111
	N	8	8	8	8	8	8	8	8	8	8	8	8
slope	PC	,352	-,097	-,359	-,568	,443	,566	-,518	,202	-,097	1	,968**	,323
	Sig. (2-tailed)	,392	,819	,382	,142	,272	,144	,188	,632	,820		,000	,435
	N	8	8	8	8	8	8	8	8	8	8	8	8
f_gradient	PC	,229	,081	-,197	-,522	,345	,512	-,517	,337	,087	,968**	1	,460
	Sig. (2-tailed)	,585	,849	,640	,185	,403	,195	,189	,414	,838	,000		,251
	N	8	8	8	8	8	8	8	8	8	8	8	8
RC	PC	-,176	,475	,365	-,307	,067	,219	,081	,508	,607	,323	,460	1
	Sig. (2-tailed)	,677	,235	,374	,459	,875	,603	,849	,198	,111	,435	,251	
	N	8	8	8	8	8	8	8	8	8	8	8	8

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Annex 22. Output in SPSS for the Pearson correlation coefficients between runoff coefficient (RC) and *feses* volume per ha (m^3/ha).

Correlations

		RC	*feses* volume/ha
RC	Pearson Correlation	1	,383
	Sig. (2-tailed)		,349
	N	8	8
feses volume/ha	Pearson Correlation	,383	1
	Sig. (2-tailed)	,349	
	N	8	8

Annex 23.1 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: *feses* density, fraction of tef, catchment-averaged slope, soil depth and top width of *feses* right after establishment. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	top_width, slope, *feses*_density, tef, soil_depth[b]	.	Enter
2	.	*feses*_density	Backward (criterion: Probability of F-to-remove >= ,100).
3	.	tef	Backward (criterion: Probability of F-to-remove >= ,100).
4	.	slope	Backward (criterion: Probability of F-to-remove >= ,100).
5	.	soil_depth	Backward (criterion: Probability of F-to-remove >= ,100).
6	.	top_width	Backward (criterion: Probability of F-to-remove >= ,100).

a. Dependent Variable: RC

b. All requested variables entered.

Annex 23.2 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: *feses* density, fraction of tef, catchment-averaged slope, soil depth and top width of *feses* right after establishment. Output in SPSS for the coefficients of the models with its significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-25,141	22,453		-1,120	,379
	tef	-,100	,130	-,334	-,771	,521
	soil_depth	41,823	27,630	,739	1,514	,269
	*feses*_density	,017	,027	,249	,612	,603
	slope	2,931	1,896	,741	1,546	,262

	top_width	52,536	36,311	,684	1,447	,285
2	(Constant)	-25,378	19,974		-1,271	,293
	tef	-,118	,113	-,392	-1,040	,375
	soil_depth	45,121	24,111	,798	1,871	,158
	slope	2,949	1,687	,745	1,748	,179
	top_width	62,789	28,664	,818	2,190	,116
3	(Constant)	-20,141	19,526		-1,031	,361
	soil_depth	38,166	23,401	,675	1,631	,178
	slope	2,100	1,491	,531	1,408	,232
	top_width	54,197	27,729	,706	1,955	,122
4	(Constant)	-1,917	15,990		-,120	,909
	soil_depth	22,062	22,330	,390	,988	,369
	top_width	52,551	30,303	,685	1,734	,143
5	(Constant)	12,008	7,538		1,593	,162
	top_width	39,034	26,985	,508	1,447	,198
6	(Constant)	21,718	3,688		5,888	,001

a. Dependent Variable: RC

Annex 24.1 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: stone bund density, soil depth, fraction of tef and barley, and depth of *feses* right after establishment. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	barley, depth_*feses*, SB_density, soil_depth, tef[b]	.	Enter
2	.	SB_density	Backward (criterion: Probability of F-to-remove >= ,100).
3	.	soil_depth	Backward (criterion: Probability of F-to-remove >= ,100).
4	.	tef	Backward (criterion: Probability of F-to-remove >= ,100).
5	.	barley	Backward (criterion: Probability of F-to-remove >= ,100).
6	.	depth_*feses*	Backward (criterion: Probability of F-to-remove >= ,100).

a. Dependent Variable: RC

b. All requested variables entered.

Annex 24.2 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: stone bund density, soil depth, fraction of tef and barley, and depth of *feses* right after establishment. Output in SPSS for the coefficients of the models with its significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	13,270	33,703		,394	,732
	SB_density	-,006	,037	-,134	-,177	,876
	tef	,064	,263	,215	,245	,830
	soil_depth	-9,337	48,149	-,165	-,194	,864
	depth_*feses*	94,899	164,397	,429	,577	,622
	barley	,470	1,358	,352	,346	,762
2	(Constant)	8,633	17,391		,496	,654
	tef	,050	,206	,166	,242	,824
	soil_depth	-4,197	31,562	-,074	-,133	,903
	depth_*feses*	101,862	131,326	,460	,776	,494
	barley	,438	1,108	,328	,395	,719
3	(Constant)	6,949	10,351		,671	,539
	tef	,039	,165	,131	,238	,823
	depth_*feses*	108,001	106,784	,488	1,011	,369
	barley	,350	,773	,262	,453	,674
4	(Constant)	7,893	8,612		,917	,401
	depth_*feses*	120,923	82,857	,546	1,459	,204
	barley	,222	,499	,166	,444	,676
5	(Constant)	7,951	8,015		,992	,359
	depth_*feses*	134,305	71,828	,607	1,870	,111
6	(Constant)	21,718	3,688		5,888	,001

a. Dependent Variable: RC

Annex 25.1 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: *feses* density, surface stoniness, the fraction of millet, *feses* gradient, and depth of *feses* right after establishment. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	depth_*feses*, *feses*_gradient, *feses*_density, stoniness, millet[b]	.	Enter
2	.	millet	Backward (criterion: Probability of F-to-remove >= .100).
3	.	*feses*_gradient	Backward (criterion: Probability of F-to-remove >= .100).
4	.	*feses*_density	Backward (criterion: Probability of F-to-remove >= .100).
5	.	stoniness	Backward (criterion: Probability of F-to-remove >= .100).
6	.	depth_*feses*	Backward (criterion: Probability of F-to-remove >= .100).

a. Dependent Variable: RC

b. All requested variables entered.

Annex 25.2 Outcome of multiple regression analysis by the backward procedure with runoff coefficient (RC) as dependent variable and the following independent variables: *feses* density, surface stoniness, the fraction of millet, *feses* gradient, and depth of *feses* right after establishment. Output in SPSS for the coefficients of the models with its significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3.322	20.800		-.160	.888
	*feses*_density	.020	.036	.304	.562	.631
	stoniness	.101	.227	.255	.444	.701
	millet	.016	.174	.054	.094	.934
	*feses*_gradient	50.029	111.675	.289	.448	.698
	depth_*feses*	111.985	117.976	.506	.949	.443
2	(Constant)	-2.292	14.459		-.159	.884
	*feses*_density	.021	.029	.319	.750	.508
	stoniness	.106	.180	.269	.591	.596
	*feses*_gradient	44.045	74.999	.255	.587	.598
	depth_*feses*	107.546	88.428	.486	1.216	.311
3	(Constant)	-4.798	12.633		-.380	.723
	*feses*_density	.025	.025	.377	.999	.374
	stoniness	.167	.135	.421	1.232	.285
	depth_*feses*	112.244	80.531	.507	1.394	.236
4	(Constant)	-1.090	12.071		-.090	.932
	stoniness	.130	.130	.330	1.001	.363
	depth_*feses*	146.505	72.838	.662	2.011	.100
5	(Constant)	7.951	8.015		.992	.359
	depth_*feses*	134.305	71.828	.607	1.870	.111
6	(Constant)	21.718	3.688		5.888	.001

a. Dependent Variable: RC

Annex 26. Outcome of multivariate regression analysis for runoff coefficient as dependent variable and the following independent variables: rain fallen the day of the event (R1), half day antecedent rainfall (R2), one day antecedent rainfall (R3) and five days of antecedent rainfall (R4). Output in SPSS for the model summaries.

Model Summary catchment 1

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,558[a]	,311	,262	,311	6,334	,025
2	,675[b]	,455	,371	,144	3,427	,087
3	,687[c]	,471	,339	,016	,367	,556
4	,687[d]	,472	,280	,000	,009	,927

a. Predictors: (Constant), R1C1

b. Predictors: (Constant), R1C1, R2C1

c. Predictors: (Constant), R1C1, R2C1, R3C1

d. Predictors: (Constant), R1C1, R2C1, R3C1, R4C1

Model Summary catchment 2

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,612[a]	,375	,330	,375	8,393	,012
2	,618[b]	,382	,287	,008	,159	,696
3	,685[c]	,469	,337	,087	1,970	,186
4	,687[d]	,472	,280	,002	,047	,832

a. Predictors: (Constant), R1C2

b. Predictors: (Constant), R1C2, R2C2

c. Predictors: (Constant), R1C2, R2C2, R3C2

d. Predictors: (Constant), R1C2, R2C2, R3C2, R4C2

Model Summary catchment 3

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,397[a]	,158	,081	,158	2,059	,179
2	,464[b]	,216	,059	,058	,739	,410
3	,469[c]	,220	-,041	,004	,045	,836

a. Predictors: (Constant), R1C3

b. Predictors: (Constant), R1C3, R2C3

c. Predictors: (Constant), R1C3, R2C3, R3C3

Model Summary catchment 4

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,321[a]	,103	,022	,103	1,266	,285
2	,741[b]	,550	,460	,446	9,913	,010
3	,777[c]	,604	,472	,054	1,234	,295
4	,788[d]	,621	,432	,017	,365	,562

a. Predictors: (Constant), R1C4

b. Predictors: (Constant), R1C4, R2C4

c. Predictors: (Constant), R1C4, R2C4, R3C4

d. Predictors: (Constant), R1C4, R2C4, R3C4, R4C4

Model Summary catchment 5

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,745[a]	,555	,525	,555	18,712	,001
2	,748[b]	,560	,497	,005	,150	,704
3	,750[c]	,562	,461	,003	,080	,782
4	,752[d]	,566	,421	,003	,094	,764

a. Predictors: (Constant), R1C5

b. Predictors: (Constant), R1C5, R2C5

c. Predictors: (Constant), R1C5, R2C5, R3C5

d. Predictors: (Constant), R1C5, R2C5, R3C5, R4C5

Model Summary catchment 6

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,051[a]	,003	-,108	,003	,024	,881
2	,336[b]	,113	-,109	,110	,991	,349
3	,379[c]	,144	-,223	,031	,254	,630
4	,748[d]	,560	,266	,416	5,673	,055

a. Predictors: (Constant), R1C6

b. Predictors: (Constant), R1C6, R2C6

c. Predictors: (Constant), R1C6, R2C6, R3C6

d. Predictors: (Constant), R1C6, R2C6, R3C6, R4C6

Model Summary catchment 7

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,159[a]	,025	-,072	,025	,258	,623
2	,226[b]	,051	-,160	,026	,245	,632
3	,247[c]	,061	-,291	,010	,085	,778
4	,281[d]	,079	-,448	,018	,135	,724

a. Predictors: (Constant), R1C7

b. Predictors: (Constant), R1C7, R2C7

c. Predictors: (Constant), R1C7, R2C7, R3C7

d. Predictors: (Constant), R1C7, R2C7, R3C7, R4C7

Model Summary catchment 9

Model	R	R Square	Adjusted R Square	Change Statistics		
				R Square Change	F Change	Sig. F Change
1	,093[a]	,009	-,090	,009	,088	,773
2	,190[b]	,036	-,178	,027	,256	,625
3	,336[c]	,113	-,219	,077	,695	,429
4	,561[d]	,315	-,077	,201	2,058	,195

a. Predictors: (Constant), R1C9

b. Predictors: (Constant), R1C9, R2C9

c. Predictors: (Constant), R1C9, R2C9, R3C9

d. Predictors: (Constant), R1C9, R2C9, R3C9, R4C9

Annex 27. Output of linear regression analysis with the time-averaged runoff coefficient (RC) as dependent variable and the catchment area (ha) as independent variable for catchments 1, 2, 3, 4, 5, 6, 7, and 9. The relation is found to be not significant at a 0.05 significance level. Output in SPSS for the coefficient of the model with its significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	14,295	6,844		2,089	,082
	area	3,763	2,970	,459	1,267	,252

a. Dependent Variable: RC

Annex 28. Summary of linear regression analysis (y= ax + b) in SPSS for runoff coefficient as dependent variable (y) and time (in unit of days) as independent variable (x). P-values are presented under 'sig.', showing no significant a-coefficients on a 0.05 significance level. Also the coefficients of determination R^2 are presented.

catchment	a	sig.	b	sig.	R^2
1	0.174	0.663	24.365	0.057	0.01
2	-0.011	0.886	5.370	0.026	0.00
3	-0.047	0.927	39.888	0.011	0.00
4	0.234	0.220	13.087	0.031	0.13
5	-0.086	0.815	26.798	0.017	0.00
6	0.595	0.148	1.075	0.927	0.22
7	-0.123	0.625	15.511	0.033	0.02
9	0.522	0.388	14.433	0.383	0.08

Annex 29.1 Outcome of the second degree polynomial regression with the normalized peak discharge (Qmax/A) as dependent variable and *feses* density as independent variable. Output in SPSS for the significance of the coefficients.

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	-5,147E-7	,000		-,419	,692
*feses*_density	3,178E-8	,000	2,626	2,292	,070
*feses*_density2	-6,466E-11	,000	-2,425	-2,116	,088

a. Dependent Variable: Qmax_norm

Annex 29.2 Outcome of the linear regression analysis with the normalized peak discharge (Qmax/A) as dependent variable and stone bund density as independent variable. Output in SPSS for the significance of the coefficients.

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	2,931E-6	,000		2,218	,068
	SB_density	-3,060E-9	,000	-,350	-,915	,396

a. Dependent Variable: Qmax_norm

Annex 30. Date of runoff events (and time when more runoff events occurred during one day over the different study areas) and the corresponding calculated kurtosis, velocity of rise time (VRT), peak discharge over base time (QBT), and normalized peak discharge (Q_{max}/A) determined from the hydrograph of each event, for catchments 1, 2, 3, 4, 5, 6, 7 and 9.

CATCHMENT 1				
date runoff event	kurtosis	VRT (m³/(10^-3*s*m³))	QBT (m³/s/hour)	Q_{max}/A (m/s)
16/07	-0.47	3.06E-07	0.2365	1.12E-05
24/07	-1.16	3.15E-07	0.0510	1.10E-06
30/07	-0.96	3.15E-07	0.0665	2.58E-06
31/07	0.06	9.54E-08	0.0283	1.10E-06
04/08	-0.09	3.70E-07	0.0460	2.58E-06
05/08	-2.01	4.17E-08	0.0061	2.09E-07
07/08 (12:00)	4.32	5.31E-07	0.1246	8.05E-06
08/08	1.17	3.18E-07	0.0587	2.02E-06
15/08 (15:00)	1.27	1.33E-07	0.0507	1.53E-06
22/08	0.98	3.23E-07	0.0284	7.33E-07
25/08	-0.56	2.11E-07	0.0267	5.75E-07
30/08	-1.88	9.84E-08	0.0121	2.09E-07
02/09	1.01	7.39E-07	0.1247	5.37E-06
03/09	2.38	5.12E-07	0.1311	6.21E-06
mean	0.29	3.08E-07	0.0708	3.10E-06
STDEV	1.66	2.06E-07	0.0557	3.35E-06
min	-2.01	4.17E-08	0.0061	2.09E-07
max	4.32	7.39E-07	0.2365	1.12E-05

CATCHMENT 2				
date runoff event	kurtosis	VRT (m³/(10^-3*s*m³))	QBT (m³/s/hour)	Q_{max}/A (m/s)
18/07 (9:00)	4.69	1.88E-07	0.0663	1.25E-06
24/07	-3.58	3.13E-08	0.0077	1.09E-07
30/07	-2.3	9.95E-08	0.0573	8.14E-07
31/07	-0.03	2.21E-08	0.0108	2.55E-07
01/08	-0.38	1.33E-07	0.0170	3.21E-07
04/08	0.8	1.57E-08	0.0077	1.09E-07
06/08	-0.85	3.69E-08	0.0128	4.85E-07
07-Aug 12:00)	-0.34	1.37E-07	0.0601	2.27E-06
08/08	0.59	7.35E-08	0.0146	4.85E-07
15/08 (9:00)	-2.43	5.14E-09	0.0054	7.64E-08
15/08 (13:00)	-0.93	2.22E-08	0.0167	9.48E-07

22/08	-0.82	2.11E-08	0.0027	5.07E-08
24/08	-0.39	1.55E-08	0.0045	1.49E-07
25/08	-0.43	2.86E-08	0.0038	1.09E-07
26/08	-0.43	1.38E-08	0.0038	1.09E-07
02/09	-0.3	9.15E-09	0.0085	3.21E-07
mean	-0.75	5.33E-08	0.0187	4.92E-07
STDEV	2.05	5.67E-08	0.0216	6.11E-07
min	-5.57	5.14E-09	0.0027	5.07E-08
max	4.69	1.88E-07	0.0663	2.27E-06

CATCHMENT 3				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT (m^3/s/hour)	Q_{max}/A (m/s)
16/07	3.8	1.45E-06	4.5553	5.41E-05
18/07 (9:00)	2.86	2.05E-07	0.1437	1.71E-06
23/07 (17:00)	-2.8	1.84E-07	0.1335	1.58E-06
24/07	-1.96	9.93E-08	0.0550	5.45E-07
30/07	-1.31	7.02E-07	0.4251	5.89E-06
05/08	0.87	5.36E-08	0.0152	8.12E-07
06/08	-1.2	2.08E-07	0.0732	3.48E-06
07/08 (08:00)	-0.65	9.61E-09	0.0078	1.70E-07
07/08 (12:00)	1.79	4.89E-08	0.0651	3.48E-06
14/08 (09:00)	3.76	1.33E-07	0.0676	3.48E-06
15/08 (15:00)	4.74	6.08E-07	0.1889	7.10E-06
22/08	0.64	9.23E-08	0.0103	2.64E-07
24/08	-0.2	5.31E-08	0.0421	1.83E-06
25/08	-0.23	5.76E-08	0.0102	3.02E-07
mean	0.72	2.79E-07	0.4138	6.05E-06
STDEV	2.26	3.97E-07	1.1970	1.40E-05
min	-2.8	9.61E-09	0.0078	1.70E-07
max	4.74	1.45E-06	4.5553	5.41E-05

CATCHMENT 4				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT (m^3/s/hour)	Q_{max}/A (m/s)
18/07 (9:00)	0.51	8.25E-09	0.0029	1.17E-07
18/07 (15:00)	3.17	1.53E-09	0.0014	2.38E-08
23/07 (17:00)	-1.52	1.30E-08	0.0088	2.72E-07
30/07	-1.11	8.66E-08	0.0249	7.09E-07
31/07	-0.87	8.71E-08	0.0282	1.00E-06
03/08	-1.48	7.05E-08	0.0150	5.34E-07
04/08	-1.74	3.71E-09	0.0089	5.47E-07

06/08	-1.36	8.26E-08	0.0166	7.51E-07
07/08 (12:00)	-0.79	6.02E-08	0.0256	9.11E-07
14/08 (13:00)	0.89	3.59E-08	0.0145	7.94E-07
15/08 (15:00)	-1.05	5.67E-08	0.0229	6.53E-07
24/08	0.13	7.95E-08	0.0143	3.73E-07
02/09	-0.96	2.58E-08	0.0199	7.09E-07
03/09	-1.6	1.23E-08	0.0273	9.72E-07
mean	-0.56	4.46E-08	0.0165	5.98E-07
STDEV	1.29	3.35E-08	0.0088	3.06E-07
min	-1.74	1.53E-09	0.0014	2.38E-08
max	3.17	8.71E-08	0.0282	1.00E-06

CATCHMENT 5				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT (m^3/s/hour)	Q_{max}/A (m/s)
18/07 (9:00)	-0.21	4.17E-08	0.0124	5.71E-07
23/07 (17:00)	-1.2	1.47E-08	0.0626	1.91E-06
24/07	-1.84	3.17E-08	0.0096	2.93E-07
31/07	-0.45	3.60E-07	0.0626	4.15E-06
03/08	0.33	5.58E-08	0.0119	4.23E-07
04/08	-1.34	2.57E-07	0.0319	1.79E-06
05/08	0.92	1.14E-07	0.0093	5.71E-07
06/08	0.19	4.48E-08	0.0200	1.32E-06
07/08 (12:00)	-0.91	1.69E-07	0.0317	2.58E-06
08/08	1.28	4.06E-07	0.0422	2.58E-06
09/08	-0.34	7.97E-08	0.0139	4.95E-07
14/08 (09:00)	1.22	3.81E-08	0.0099	1.67E-06
14/08 (13:00)	-0.15	3.10E-08	0.0149	2.73E-06
15/08 (15:00)	0.36	1.89E-07	0.0284	2.17E-06
22/08	0.66	1.73E-07	0.0119	4.23E-07
24/08	1.21	1.57E-07	0.0180	9.17E-07
25/08	-2.08	9.64E-08	0.0115	2.93E-07
26/08	-1.79	6.90E-08	0.0072	2.93E-07
mean	-0.23	1.29E-07	0.0228	1.40E-06
STDEV	1.07	1.14E-07	0.0174	1.12E-06
min	-2.08	1.47E-08	0.0072	2.93E-07
max	1.28	4.06E-07	0.0626	4.15E-06

CATCHMENT 6				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT (m^3/s/hour)	Q_{max}/A (m/s)
23/07 (18:00)	4.52	5.20E-08	0.0065	3.78E-07

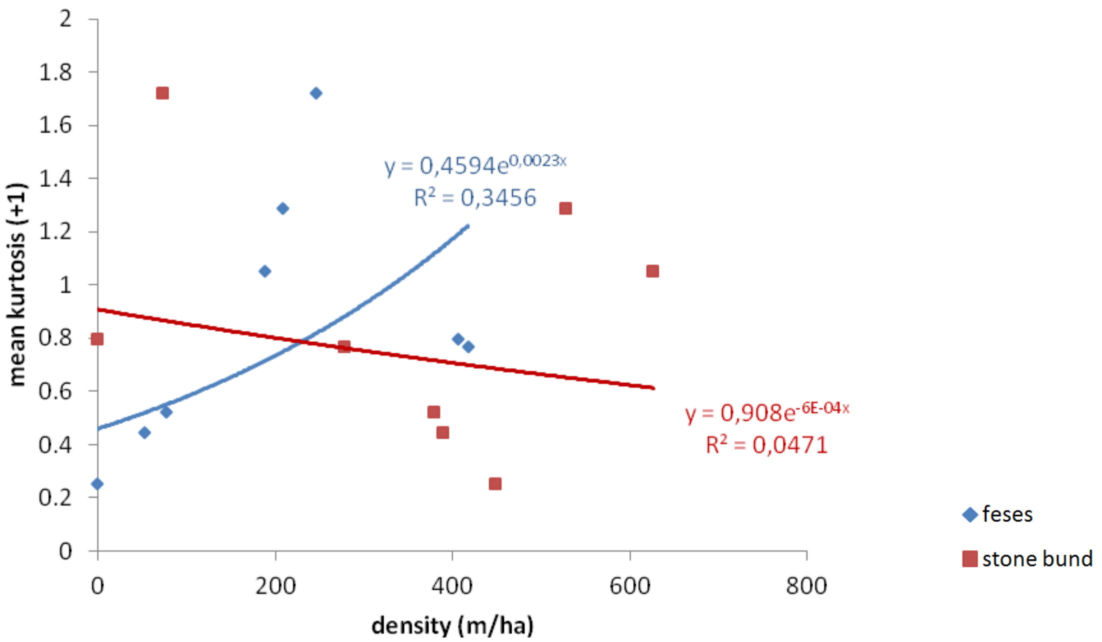
24/07	2.44	4.68E-08	0.0034	1.39E-07
03/08	-0.26	1.88E-07	0.0328	1.33E-06
06/08	-0.99	8.62E-08	0.0252	7.31E-07
07/08 (08:00)	-1.67	5.52E-08	0.0240	8.36E-07
14/08 (09:00)	-2.22	1.16E-07	0.0561	2.28E-06
15/08 (13:00)	-1.6	5.62E-08	0.0613	2.84E-06
15/08 (15:00)	0.55	2.30E-08	0.0133	3.08E-07
24/08	-1.84	4.17E-07	0.0544	2.84E-06
03/09	-0.97	3.37E-08	0.0234	9.49E-07
mean	-0.2	1.07E-07	0.0300	1.26E-06
STDEV	2.05	1.19E-07	0.0208	1.03E-06
min	-2.22	2.30E-08	0.0034	1.39E-07
max	4.52	4.17E-07	0.0613	2.84E-06

CATCHMENT 7				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT ($m^3/s/hour$)	Q_{max}/A (m/s)
23/07 (17:00)	-0.45	8.27E-08	0.0075	6.90E-07
23/07 (18:00)	-0.47	5.98E-08	0.0057	4.60E-07
24/07	-0.81	7.92E-08	0.0052	4.17E-07
30/07	-0.91	7.20E-08	0.0076	1.22E-06
01/08	-0.48	5.45E-08	0.0065	5.95E-07
03/08	-1.21	2.51E-08	0.0047	3.75E-07
04/08	1.47	3.39E-08	0.0045	2.59E-07
06/08	-1.14	1.23E-07	0.0110	5.03E-07
07/08 (08:00)	0.7	2.20E-08	0.0067	4.60E-07
08/08	1.21	4.08E-08	0.0066	3.75E-07
14/08 (09:00)	-1.71	1.69E-08	0.0080	4.60E-07
14/08 (13:00)	0.27	1.11E-08	0.0082	3.75E-07
15/08 (9:00)	-1.86	3.80E-08	0.0100	6.90E-07
15/08 (15:00)	0.11	4.78E-08	0.0089	1.22E-06
15/08 (18:00)	-1.22	5.75E-08	0.0118	9.46E-07
03/09	-1.12	4.92E-08	0.0102	1.06E-06
mean	-0.48	5.09E-08	0.0077	6.32E-07
STDEV	0.95	2.88E-08	0.0022	3.14E-07
min	-1.86	1.11E-08	0.0045	2.59E-07
max	1.47	1.23E-07	0.0118	1.22E-06

CATCHMENT 9				
date runoff event	kurtosis	VRT ($m^3/(10^{-3}*s*m^3)$)	QBT ($m^3/s/hour$)	Q_{max}/A (m/s)
16/07	4.95	1.49E-08	0.0052	9.13E-07

31/07	-1.97	1.50E-07	0.0181	2.40E-06
01/08	-1.01	8.50E-08	0.0078	1.04E-06
05/08	-1.37	3.63E-08	0.0044	4.59E-07
06/08	1.41	5.18E-08	0.0038	6.20E-07
07/08 (12:00)	-0.14	4.93E-08	0.0079	2.32E-06
08/08	0.09	2.29E-07	0.0106	3.14E-06
14/08 (09:00)	-0.82	5.82E-08	0.0043	2.72E-06
15/08 (15:00)	1.62	1.19E-07	0.0099	2.48E-06
24/08	-0.82	1.41E-08	0.0015	2.01E-07
02/09	-1.37	3.66E-08	0.0062	1.10E-06
mean	0.05	7.67E-08	0.0072	1.58E-06
STDEV	1.88	6.57E-08	0.0045	1.08E-06
min	-1.97	1.41E-08	0.0015	2.01E-07
max	4.95	2.29E-07	0.0181	3.14E-06

Annex 31.1 Exponential relations between kurtosis (summed up by one) and stone bund and *feses* density.



Annex 31.2 Significance of coefficients for the exponential relation between kurtosis and stone bund density (output in SPSS).

Model Summary and Parameter Estimates

Dependent Variable: kurtosis_plus1

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	,047	,295	1	6	,607	,907	-,001

The independent variable is SB_density.

Annex 31.3 Significance of coefficients for the exponential relation between kurtosis and *feses* density (output in SPSS).

Model Summary and Parameter Estimates

Dependent Variable: kurtosis_plus1

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	,346	3,176	1	6	,125	,459	,002

The independent variable is *feses*_density.

Annex 32.1 Significance of coefficients for the second degree polynomial relation between kurtosis and *feses* density (output in SPSS).

Coefficients[a]

	Unstandardized Coefficients		t	Sig.
	B	Std. Error		
(Constant)	-,946	,189	-5,017	,004
*feses*_density	,010	,002	4,760	,005
*feses*_density2	-2,005E-5	,000	-4,273	,008

a. Dependent Variable: kurtosis

Annex 32.2 Significance of coefficients of the linear relation between kurtosis and stone bund density (output in SPSS).

Coefficients[a]

	Unstandardized Coefficients		t	Sig.
	B	Std. Error		
(Constant)	,031	,353	,087	,934
SB_density	-,001	,001	-,574	,587

a. Dependent Variable: kurtosis

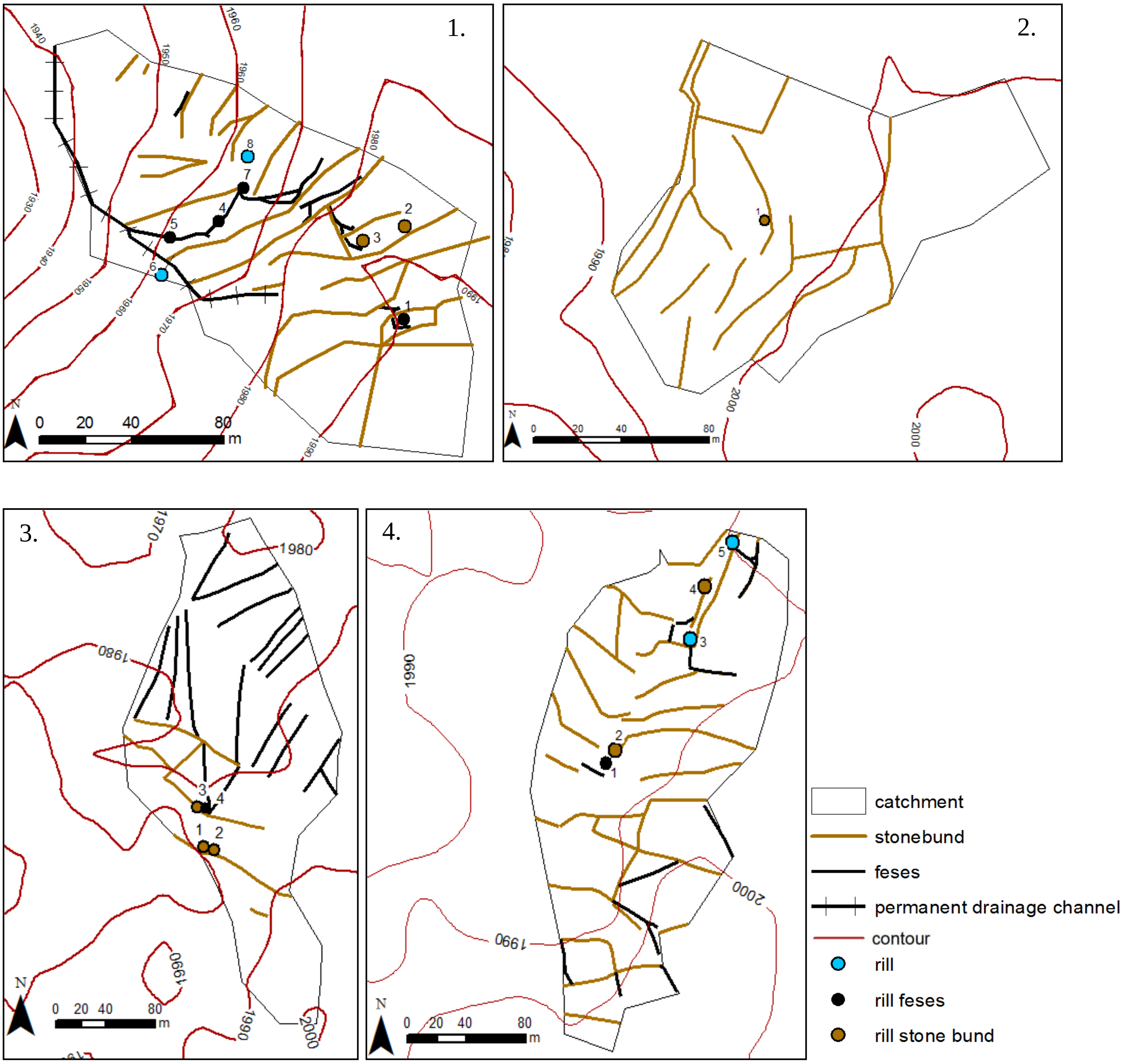
Annex 33. Dimensions of the measured rill erosion (length, width, depth) and the calculated total volume (m^3) of rill erosion for each study area. Rills with the same starting point have the same rill number. Rills originating from misconstructed *feses* (*) or misconstructed stone bunds (°) are marked.

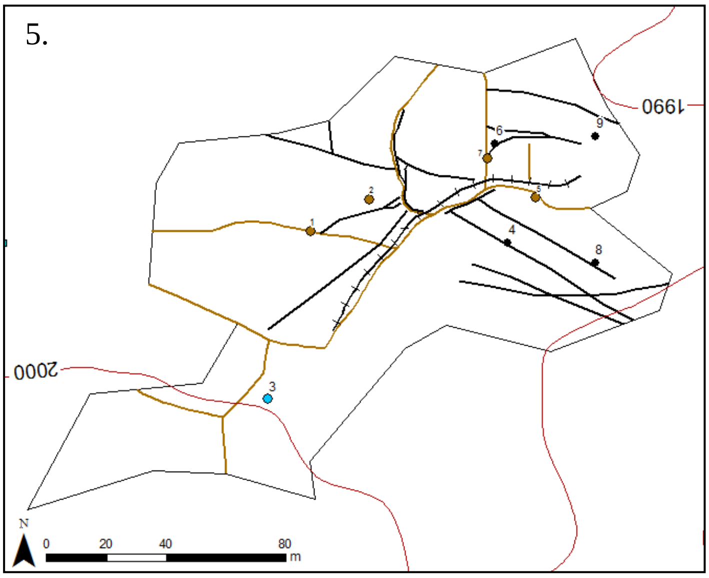
rill	length (m)	width (m)	depth (m)	total volume (m^3)
catchment 1				
1*	3.60	0.40	0.07	0.10
2°	5.50	0.30	0.10	0.17
2°	4.00	0.37	0.10	0.15
3°	2.70	0.05	0.10	0.01
4*	7.50	0.26	0.07	0.14
5*	2.50	0.30	0.06	0.05
5*	2.50	0.33	0.10	0.08
6	6.00	0.40	0.10	0.24
7*	3.60	1.50	0.10	0.54
7*	7.15	0.50	0.07	0.25
8	12.65	0.30	0.05	0.19
total rill volume (m^3)				1.91
catchment 2				
1°	5.60	0.48	0.07	0.19
1°	4.80	0.35	0.07	0.12
total rill volume (m^3)				0.31
catchment 3				
1°	3.40	0.30	0.07	0.07
2°	9.00	0.40	0.10	0.36
3°	9.40	0.40	0.06	0.23
4*	3.00	0.35	0.04	0.04
5*	5.00	0.20	0.13	0.13
total rill volume (m^3)				0.83
catchment 4				
1*	3.30	1.74	0.10	0.57
2	10.53	0.27	0.05	0.14
2°	9.00	0.27	0.05	0.12
3	7.00	1.27	0.05	0.44
3	4.80	1.43	0.07	0.48
4°	11.20	0.27	0.04	0.12
5	6.70	0.30	0.05	0.10
total rill volume (m^3)				1.98
catchment 5				
1°	3.50	0.54	0.15	0.28
2°	9.00	0.75	0.10	0.68
3	7.50	0.50	0.09	0.34
3	12.20	0.35	0.10	0.43

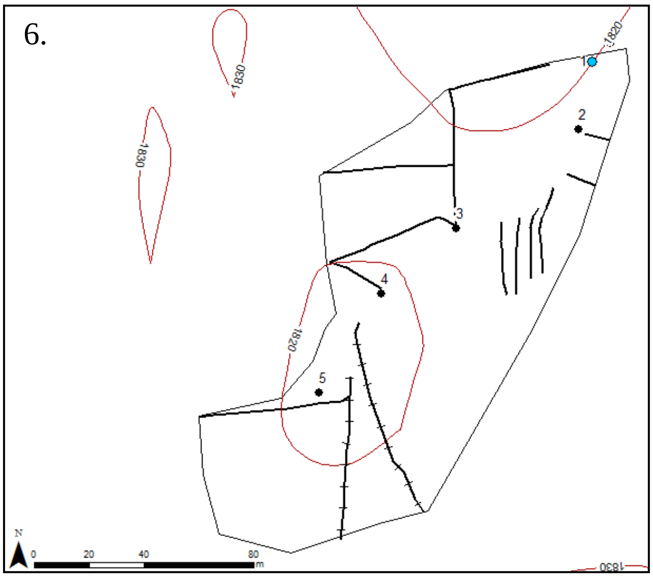
4*	13.00	0.22	0.06	0.17
4*	13.00	0.22	0.06	0.17
4*	13.00	0.22	0.06	0.17
5*	8.30	0.30	0.08	0.20
5*	8.30	0.35	0.01	0.03
5*	7.20	0.24	0.06	0.10
6*	7.00	0.20	0.03	0.04
7°	11.75	1.68	0.13	2.57
8*	6.70	0.50	0.10	0.34
9*	8.00	0.30	0.14	0.34
9*	8.40	0.50	0.12	0.50
9*	5.30	0.46	0.08	0.20
			total rill volume (m^3)	6.55
		catchment 6		
1	8.70	1.00	0.09	0.78
2*	6.40	0.70	0.07	0.31
3*	5.00	0.27	0.07	0.09
4*	14.30	0.20	0.06	0.17
5*	10.80	0.23	0.04	0.10
			total rill volume (m^3)	2.37
		catchment 7		
1	23.70	1.50	0.07	2.49
2	23.70	0.26	0.04	0.25
2	10.30	0.16	0.04	0.07
2	7.60	0.20	0.02	0.03
3	14.00	0.25	0.02	0.07
3	14.00	0.25	0.02	0.07
4	22.00	0.46	0.03	0.30
5	20.20	0.44	0.03	0.27
6	18.16	0.40	0.05	0.36
6	5.20	0.10	0.04	0.02
6	5.20	0.10	0.04	0.02
6	7.50	0.12	0.04	0.04
6	7.50	0.12	0.04	0.04
7*	13.20	0.70	0.08	0.74
8*	14.00	0.12	0.04	0.07
			total rill volume (m^3)	5.15
		catchment 8		
1*	5.70	0.66	0.14	0.53
1*	5.00	0.70	0.10	0.35
2	4.70	0.45	0.12	0.25
2	7.30	0.20	0.13	0.19
2	3.40	0.30	0.10	0.10
2	3.40	0.30	0.10	0.10

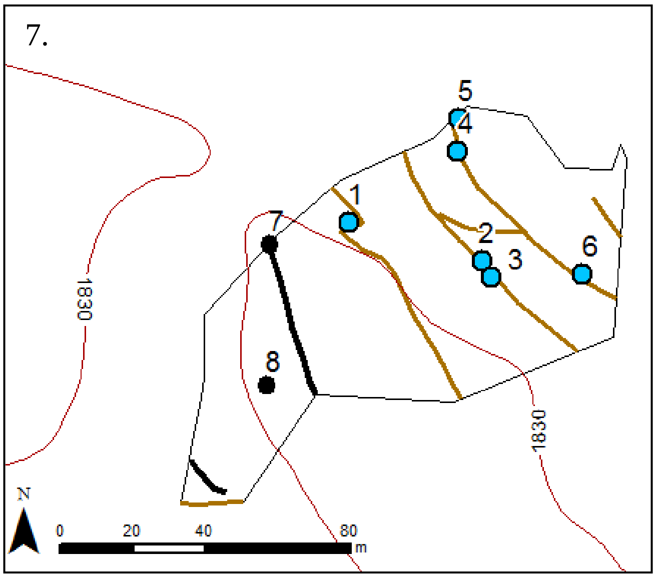
2	7.60	0.35	0.13	0.35
2	10.70	0.26	0.13	0.36
3	15.00	0.52	0.14	1.09
3	2.00	0.50	0.10	0.10
total rill volume (m^3)				3.42
catchment 9				
1	1.00	0.26	0.07	0.02
2*	13.40	0.37	0.12	0.59
total rill volume (m^3)				0.61
catchment 10				
1*	3.50	0.25	0.07	0.06
2*	16.00	0.37	0.10	0.59
3*	23.70	0.37	0.14	1.23
4	13.60	0.26	0.14	0.50
5*	24.60	0.38	0.12	1.12
total rill volume (m^3)				3.50

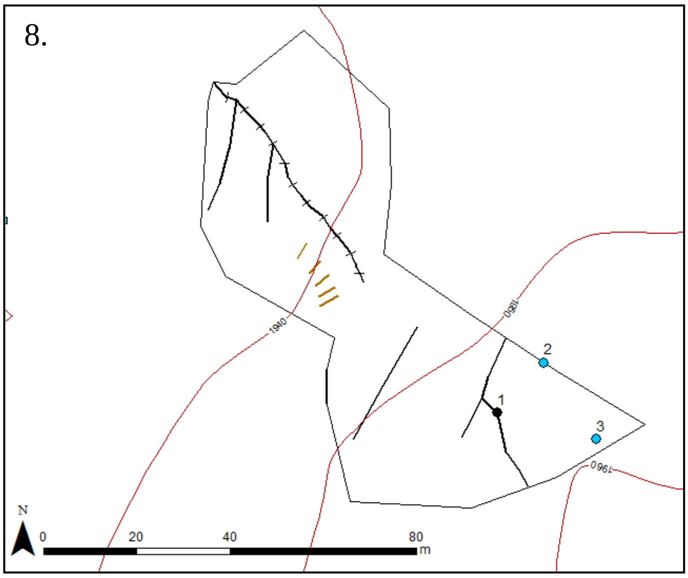
Annex 34. Location of the starting point of rills in the ten study areas. Rills originating from misconstructed *feses* or stone bunds have been marked.

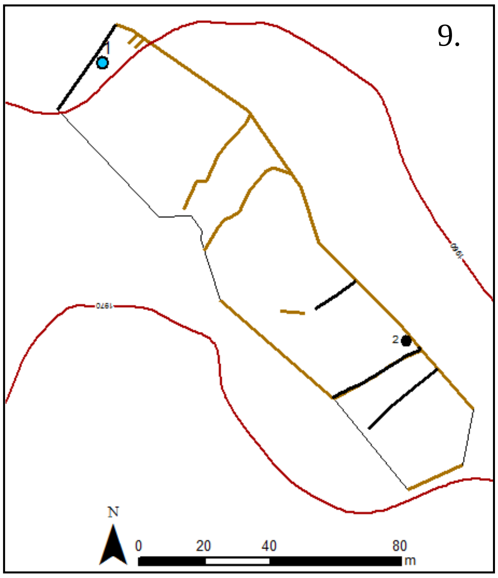


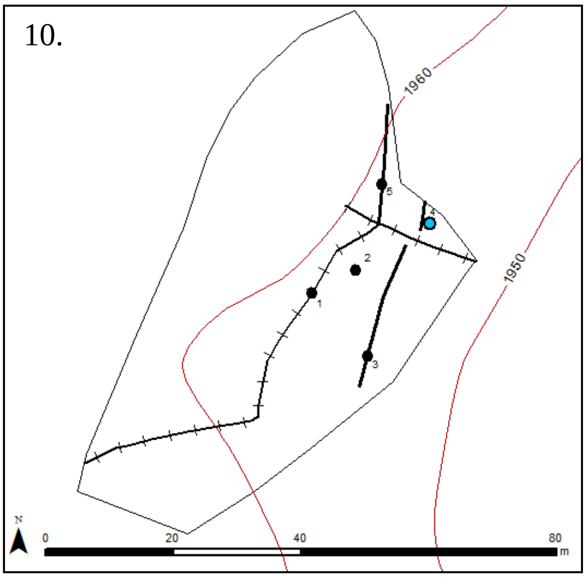

5.
1990
2000
N
0
20
40
80
m


6.
1830
1820
N
0
20
40
80
m


7.
1830
1830
N
0
20
40
80
m


8.
N
0
20
40
80
m


9.
N
0
20
40
80
m


10.
1960
1950
N
0
20
40
80
m

Annex 35. Output in SPSS for Pearson correlation coefficients (PC) between the following catchment-averaged characteristics of the ten study areas in Wanzaye (Ethiopia, 2013): stone bund density (SBD), *feses* density (FD), fraction of cultivated barley, millet or tef, surface stoniness (stoniness), soil depth, top width of *feses* (top width), depth of *feses* (depth_f), silt/clay ratio (silt_clay), bulk density (BD), catchment-averaged slope (slope, °), angle between the constructed *feses* and the contour line (angle_contour), *feses* gradient (f_gradient), and total rill volume per ha (TRA) for the ten subcatchments in Wanzaye (Ethiopia, 2013). Data of all study areas is included (N=10).

Correlations

		SBD	FD	barley	millet	tef	stoniness	soil_depth	top_width	depth_f	silt_clay	BD	slope	angle_ contour	f_gradient	TRA
SBD	PC	1	-.721*	-.463	-.053	.373	.205	-.049	.325	-.172	-.191	.148	-.170	.749*	.276	-.498
	Sig. (2-tailed)		.019	.178	.883	.288	.570	.893	.360	.634	.598	.683	.640	.020	.440	.143
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
FD	PC	-.721*	1	.531	-.246	-.262	.145	-.395	.242	.416	.257	-.128	.374	-.671*	-.039	.594
	Sig. (2-tailed)	.019		.114	.493	.464	.690	.259	.501	.232	.474	.724	.288	.048	.915	.070
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
barley	PC	-.463	.531	1	-.351	-.462	.307	-.291	.064	.113	.344	-.274	.652*	-.174	-.126	.661*
	Sig. (2-tailed)	.178	.114		.319	.179	.388	.415	.860	.756	.330	.443	.041	.654	.728	.038
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
millet	PC	-.053	-.246	-.351	1	-.638*	-.256	.316	-.441	-.330	-.447	-.387	-.664*	-.053	-.420	-.589
	Sig. (2-tailed)	.883	.493	.319		.047	.475	.374	.202	.352	.195	.269	.036	.892	.227	.073
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
tef	PC	.373	-.262	-.462	-.638*	1	-.169	.083	.232	.148	.176	.635*	.014	.172	.354	.060
	Sig. (2-tailed)	.288	.464	.179	.047		.642	.819	.518	.683	.628	.048	.969	.659	.316	.869
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
stoniness	PC	.205	.145	.307	-.256	-.169	1	-.810**	.179	-.078	.011	-.501	.666*	.032	.343	.262
	Sig. (2-tailed)	.570	.690	.388	.475	.642		.004	.620	.831	.977	.140	.035	.934	.332	.464
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
soil_depth	PC	-.049	-.395	-.291	.316	.083	-.810**	1	-.298	-.053	-.163	.519	-.637*	.097	-.299	-.462

	Sig. (2-tailed)	.893	.259	.415	.374	.819	.004		.403	.885	.654	.124	.047	.803	.402	.179
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
top_width	PC	.325	.242	.064	-.441	.232	.179	-.298	1	.787**	.445	.381	.129	.684*	.345	.011
	Sig. (2-tailed)	.360	.501	.860	.202	.518	.620	.403		.007	.198	.277	.723	.042	.329	.976
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
depth_f	PC	-.172	.416	.113	-.330	.148	-.078	-.053	.787**	1	.713*	.432	-.016	.378	.064	.183
	Sig. (2-tailed)	.634	.232	.756	.352	.683	.831	.885	.007		.021	.213	.966	.316	.861	.612
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
silt_clay	PC	-.191	.257	.344	-.447	.176	.011	-.163	.445	.713*	1	.114	.085	.050	-.347	.635*
	Sig. (2-tailed)	.598	.474	.330	.195	.628	.977	.654	.198	.021		.754	.816	.899	.326	.049
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
BD	PC	.148	-.128	-.274	-.387	.635*	-.501	.519	.381	.432	.114	1	-.188	.507	.300	-.253
	Sig. (2-tailed)	.683	.724	.443	.269	.048	.140	.124	.277	.213	.754		.602	.164	.399	.481
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
slope	PC	-.170	.374	.652*	-.664*	.014	.666*	-.637*	.129	-.016	.085	-.188	1	-.121	.549	.544
	Sig. (2-tailed)	.640	.288	.041	.036	.969	.035	.047	.723	.966	.816	.602		.757	.100	.104
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
angle_ contour	PC	.749*	-.671*	-.174	-.053	.172	.032	.097	.684*	.378	.050	.507	-.121	1	.303	-.526
	Sig. (2-tailed)	.020	.048	.654	.892	.659	.934	.803	.042	.316	.899	.164	.757		.428	.146
	N	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
f_gradient	PC	.276	-.039	-.126	-.420	.354	.343	-.299	.345	.064	-.347	.300	.549	.303	1	-.266
	Sig. (2-tailed)	.440	.915	.728	.227	.316	.332	.402	.329	.861	.326	.399	.100	.428		.458
	N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10
TRA	PC	-.498	.594	.661*	-.589	.060	.262	-.462	.011	.183	.635*	-.253	.544	-.526	-.266	1
	Sig. (2-tailed)	.143	.070	.038	.073	.869	.464	.179	.976	.612	.049	.481	.104	.146	.458	

N	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10

Annex 36.1 Outcome of multiple regression analysis for total rill volume per ha by a stepwise procedure. Independent variables of the model are: *feses* density, fraction of tef, catchment-averaged soil depth and top width of *feses* right after establishment. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	silt_clay	.	Stepwise (Criteria: Probability-of-F-to-enter <= ,050, Probability-of-F-to-remove >= ,100).

a. Dependent Variable: total_rill_volume_ha

Annex 36.2 Outcome of multiple regression analysis for total rill volume per ha (TRA) by a stepwise procedure. Independent variables of the model are: *feses* density, fraction of tef, catchment-averaged soil depth and top width of *feses* right after establishment. Output in SPSS for the coefficients of the excluded variables with its significance.

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
1	*feses*_density	.462[b]	1.873	.103	.578	.934
	tef	-.053[b]	-.179	.863	-.068	.969
	soil_depth	-.369[b]	-1.412	.201	-.471	.974
	top_width	-.338[b]	-1.127	.297	-.392	.802

a. Dependent Variable: TRA

b. Predictors in the Model: (Constant), silt_clay

Annex 36.3 Outcome of multiple regression analysis for total rill volume per ha by a stepwise procedure. Independent variables of the model are: *feses* density, fraction of tef, catchment-averaged soil depth and top width of *feses* right after establishment. Output in SPSS for the coefficients of the model with their significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-6,863	4,700		-1,460	,182
	silt_clay	3,558	1,531	,635	2,324	,049

a. Dependent Variable: total_rill_volume_ha

Annex 36.4 Outcome of multiple regression analysis for total rill volume per ha by a stepwise procedure. Independent variables of the model are: *feses* density, fraction of tef, catchment-averaged soil depth and top width of *feses* right after establishment. Coefficient of determination (output in SPSS).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,635[a]	,403	,328	3,62375

a. Predictors: (Constant), silt_clay

Annex 37.1 Outcome of multiple regression analysis for total rill volume per ha (TRA) by a stepwise procedure. Independent variables of the model are: *feses* density, catchment-averaged slope (°), top width of *feses* right after establishment, and the silt/ clay ratio. Output in SPSS for the model building procedure.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	silt_clay	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: TRA

Annex 37.2 Outcome of multiple regression analysis for total rill volume per ha (TRA) by a stepwise procedure. Independent variables of the model are: *feses* density, catchment-averaged slope (°), top width of *feses* right after establishment, and the silt/ clay ratio. Output in SPSS for the coefficients of the model with their significance.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-6.863	4.700		-1.460	.182
	silt_clay	3.558	1.531	.635	2.324	.049

a. Dependent Variable: TRA

Annex 37.3 Outcome of multiple regression analysis for total rill volume per ha (TRA) by a stepwise procedure. Independent variables of the model are: *feses* density, catchment-averaged slope (°), top width of *feses* right after establishment, and the silt/ clay ratio. Coefficient of determination (output in SPSS).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.635[a]	.403	.328	3.62375

a. Predictors: (Constant), silt_clay

Annex 37.4 Outcome of multiple regression analysis for total rill volume per ha (TRA) by a stepwise procedure. Independent variables of the model are: *feses* density, catchment-averaged slope (°), top width of *feses* right after establishment, and the silt/ clay ratio. Output in SPSS for the coefficients of the excluded variables with its significance.

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
1	*feses*_density	.462[b]	1.873	.103	.578	.934
	slope	.494[b]	2.186	.065	.637	.993
	top_width	-.338[b]	-1.127	.297	-.392	.802

a. Dependent Variable: TRA

b. Predictors in the Model: (Constant), silt_clay

Annex 38. I Acknowledge the collaboration and support of all data collectors during fieldwork in Wanzaye (2013): Demelash Sente, Bisete Sendek, Abera Abate, Admase Kasie, Amlaku Ngerew, Amlaku Amberber, Gzachew Aragaw, Msa Alebachew, Gashanew Worku, Atalo Embiale, Muche Tafere, Lengerew Welelaw and especially my translator Solomon Mulatie.