UPTEC W 19 041
Examensarbete 30 hp
Juni 2019

UPPSALA UNIVERSITET

SLU

The Effect of Agricultural Intensification on Nitrate Concentrations in Shallow Groundwater in Two Watersheds in Ethiopia

Anna Larsson

ABSTRACT

The Effect of Agricultural Intensification on Nitrate Concentrations in Shallow Groundwater in Two Watersheds in Ethiopia

Anna Larsson

Sustainable intensification of agricultural will be crucial in the future to feed a growing population and address ongoing climate changes. Ethiopia is still dominated by traditional agricultural practices and the population is expected to increase from todays 110 million to 174 million in 2050, making sustainable implementations of intensified agricultural methods crucial. In this study, two watersheds with differences in agricultural intensification and geophysical attributes in Amhara region, north western Ethiopia, are evaluated based on nitrogen content in wells. An attempt to explain the differences in contamination levels of nitrate between the two watersheds are done by examining the usage of fertilisers, amount of livestock and irrigation habits as well as topography. The result showed that the less intensified watershed exceeded the WHO guidelines for nitrate more frequently than the more intensified watershed. Temporal patterns in contamination levels in specific wells could be seen in both watersheds, where the WHO guidelines being most frequently exceeded in July and September versus July and November for the watersheds respectively. No significant correlations between nitrate concentration and explaining parameters were detected in any of the watersheds. The methods used in this paper could not explain the variations in contamination levels. The results imply that the nitrate responses are very site-specific. Evaluations including more precise details on crop management and subsurface flow patterns as well as on other factors influencing contamination levels in wells, such as distance to household and cattle, are needed in further investigations as agriculture continues to intensify.

Keywords: agricultural intensification, Ethiopia**,** fertilisers, groundwater, nitrate, watershed

Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU)
Box 7014, SE-750 07 Uppsala, Sweden
ISSN 1401-5765

REFERAT

Jordbruksintensifierings effekt på nitratkoncentrationer i ytliga grundvatten i två avrinningsområden i Etiopien

Anna Larsson

En hållbar utveckling av jordbruket kommer att vara avgörande för att föda en växande befolkning och möta pågående klimatförändringar. I Etiopien domineras jordbruket av traditionella metoder och befolkningen i landet förväntas öka från dagens 110 miljoner till 174 miljoner år 2050, vilket medför att hållbara lösningar gällande bevattning och gödslingsanvändning blir viktiga. Två avrinningsområden med olika karaktär gällnade intensifiering av jordbruk och topografi i Amhara-regionen i nordvästra Etiopien utvärderas utifrån kvävekoncentrationer i brunnar. Ett försök att förklara kvävekoncentrationer görs genom att utvärdera användningen av gödslingsmedel, mängd boskap och bevattningsvanor. Resultatet visade att det mindre intensifierade avrinningsområdet överskred WHO:s riktlinjer vid fler tillfällen än den mer intensifierade. Temporala skillnader i föroreningsnivåer kunde ses i specifika brunnar i båda avrinningsområdena, där WHO:s riktlinjer överskreds mest frekvent i juli och september respektive juli och november. Inga signifikanta korrelationer mellan nitratkoncentration och förklarande faktorer påvisades i någon av avrinningsområdena. Metoden som användes i studien kunde inte förklara de variationer som förekom i brunnarnas kontamineringsnivåer. Resultaten indikerar dock att orsakerna är platsspecifika och studier baserade på mer detaljerade data om odlingsätt och markvattenflöden samt andra påverkande faktorer, såsom avstånd till hushåll och boskap behöver göras då intensifieringen av jordbruket fortskrider.

Nyckelord: avrinningsområde**,** Etiopien, grundvatten, gödslingsmedel, jordbruksintensifiering, nitrat

Institutionen för mark och miljö, Sveriges lantbruksuniversitet (SLU)
Box 7014, SE-750 07 Uppsala, Sverige
ISSN 1401-5765

PREFACE

This project was done as master thesis within the Master Programme of Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences, SLU. The data used were collected by Bahir Dar University, Ethiopia and International Water Management Institute (IWMI) as part of the Feed the Future evaluation of the relationship between "Sustainably Intensified Production Systems and Farm Family Nutrition" (SIPS-IN) and the "Innovation Laboratory for Small Scale Irrigation" (ILSSI). The SIPS-IN project (AID-OAA-L-14-00006) and the ILSSI project (AID-OAA-A-13-0005) are two cooperative research projects implemented through the United States Agency for International Development (USAID) in support of the Feed the Future program (FtF). The research was implemented under a collaborative partnership between IWMI and Bahir Dar University. The contents of the paper are the responsibility of the author and do not necessarily reflect the views of USAID or the United States government.

Supervisor for this work has been Jennie Barron and subject reviewer has been Ingmar Messing, both professors at the Department of Soil and Environment at SLU. In addition, Dr Petra Schmitter, Agricultural and Water Management Specialist at IWMI, has functioned as an extra supervisor. I am very thankful for all their encouragement and support during the project. The two months stay in Bahir Dar, Ethiopia, was financially supported by the Swedish International Development Agency (SIDA) through a Minor Field Study scholarship. The IWMI regional office in Addis Ababa, Ethiopia led by Dr. Amare Haileslassie was involved in the framing of the project and showed great support with bureaucracy issues.

I also want to send my gratitude to Dr Seifu Thilahun for his academic advise and great hospitality during the weeks at Bahir Dar University. Furthermore, I want to thank Dr Fasikaw Atanaw and Siransh Alemu Demewoz for their help during the time spent in the office at Bahir Dar University. The Master students Daniel Geletaw and Dagnew Yehualie made the filed visits to Dangishta and Robit Bata possible which I am very grateful for. PhD student Feleke Kumaz shared his data with me and I am thankful for his help. Finally, I want to thank Elin Svedberg for being my companion both in Ethiopia and Uppsala.

ETNICHAL CONSIDERATIONS

In the ILSSI project, a survey was carried out among farmers 2017. The farmers were asked for approval before participating in the survey as well as for the water sampling program that started in the beginning of 2017. Oral information about the purpose of field visits during autumn 2018 was given to survey participants before geospatial positions and information given in the survey were verified. All spatial data have been anonymised as the purpose was to identify an issue of environmental, and tentatively human, concern.

Anna Larsson
Uppsala, 2019

UPTEC W 19 041, ISSN 1401-5765
Published digitally at the Department of Earth Sciences, Uppsala University, Uppsala 2019

POPULÄRVETENSKAPLIG SAMMANFATTNIG

Jordens växande befolkning samt pågående klimatförändringar förändrar förutsättningarna för att förse mänskligheten med de två basala behoven mat och vatten. År 2050 beräknas jordens invånarantal nå 9,8 miljarder och en stor del av denna befolkningsökning förväntas ske i områden som historiskt sett har haft problem med matförsörjningen. För att möta framtidens utmaningar gällande vatten och matproduktion krävs det att de begränsande resurser som finns att tillgå utnyttjas på bästa sätt.

Etiopien är beläget på Afrikas horn i nordöstra delen av kontinenten och förväntas ha en befolkningsökning på runt 60 miljoner fram till år 2050. Jordbruket i Etiopien domineras av traditionella metoder och uppskattas vara huvudsaklig försörjningskälla åt ca 70% av den i dagsläget 110 miljoner stora befolkningen. Klimatet i Etiopien varierar beroende på geografiskt läge, men består i regel av en regnperiod och en torrperiod. Historiskt sett har landet drabbats av matunderskott orsakad av långa torrperioder varav den största i närtid skedde 1984–1985 då runt en miljon människor beräknas fått sätta livet till. En hållbar utveckling av jordbruksmetoder för att säkra framtidens matproduktion är således viktig för att säkerställa befolkningens hälsa. Intensifiering av jordbruk kan innefatta införande av bevattningsmetoder för att möjliggöra odling i torrperioder och/eller en ökande användning av gödslingsmedel för att förstärka produktiviteten. Kombinationen gödslingsmedel och vatten, både i regn och torrperiod, riskerar dock att resultera i en urlakning av näringsämnen från jord till vattentäkter.

I denna studie har brunnars vattenkvalitet från två avrinningsområden i nordöstra Etiopien utvärderats. De båda avrinningsområdena domineras av jordbruksmark men skiljer sig åt gällande topografi och jordbrukets intensitet. Förhöjda och hälsofarliga halter av ämnet nitrat återfanns i några av brunnarna vilket resulterade i funderingar om jordbrukets eventuella inverkan på kontamineringsnivåerna. Månadsvis provtagning av vattenkvaliteten i ett 20-tal brunnar i vartdera avrinningsområde samlades in 2017 och samma år genomfördes även en intervjustudie bland jordbrukare inom de båda avrinningsområdena. I intervjustudien samlades bland annat information om djurhållning, gödslingsvanor och vattenanvändning in. I detta arbete kombinerades vattenkvalitetdata med svaren från intervjustudien med förhoppningen att förklara de geografiska och temporala skillnader som setts i brunnsvattnet. Resultatet visade att det mindre intensifierade avrinningsområdet hade högre nitrathalter i jämförelse med det mer intensifierade området. WHO:s riktlinjer gällande nitratkoncentration i dricksvatten överskreds flest gånger i den mindre intensifierade området. Temporala skillnader i nitratkoncentration för specifika brunnar kunde ses i båda avrinningsområdena men inga samband mellan nitratkoncentration och de undersökta parametrarna gödselanvändning, regnmängd och tillrinningsarea kunde ses.

TABLE OF CONTENTS

1 INTRODUCTION

The world is facing a growing population going from todays 7.6 billion reaching for about 9.8 billion in 2050 (United Nations, 2017). A growing population demands a higher food supply which puts pressure on the agriculture sector to feed the people. Consequently, a sustainable handling of limited natural resources, such as water and soils suitable for agriculture, will be crucial in the future. To address this issue, sustainable management of water in food production systems is necessary. The development of sustainable agricultural water strategies is an important part for building resilience in food production systems and enables a sustainable intensification of agriculture. Irrigation is one way to intensify agriculture and produce food during parts of the year when water supply is the limiting factor. This could expand the growing season in various regions around the world, especially those with a distinctive wet and dry period. Ethiopia, located in the north-eastern part of Africa, is one of those regions with distinctive wet and dry seasons and being the source of the Blue Nile, potential resources for water abstraction is present. Furthermore, Ethiopia is together with eight other countries assigned to contribute to half of the world's population growth between 2017-2050, making the development in the region of great interest (UN, 2017).

The watershed of Lake Tana, the largest lake in Ethiopia and the source of the Blue Nile, is recognised as an important resource for its fertility and access of water (European Space Agency, 2014 & Mulugeta, 2013). The region has been identified by the Ethiopian government as one of the most important areas for socioeconomic developments regarding the good water and land resources (Mulugeta, 2013). To meet the future food demand, sustainable agricultural is of particular importance in such areas, but are necessary in the entire sector which today employs about 70% of the Ethiopian labour force (World Bank Data, 2019). According to Schmitter (2018) smallholder irrigation using shallow groundwater is expanding rapidly in Lake Tana basin. Shallow groundwater availability has a strong spatial-temporal variation in the watershed influencing the potential of its use in irrigation as well as domestic purposes. Whilst shallow groundwater has been mainly used for livestock, drinking and domestic use in the past, the recent development of irrigated agriculture has increased the water demand during the dry season. As irrigation expands in the area, contamination of shallow groundwater caused by agricultural management becomes a risk (Schmitter, 2018). Knowledge about groundwater quality in the area is therefore of importance.

Dangshita and Robit Bata, are two watersheds in the adjacency of lake Tana in Amhara Region where an extensive data collection of water quality parameters has been done during 2017 as part of project named SIPS IN[1]. Both watersheds are dominated by agricultural land use but with different geophysical attributes and degree of intensified agriculture, which make the areas to contrasting study sites. In addition, a survey evaluating water abstraction habits, holding of animals, use of agrochemicals and the farmers idea about their water quality was

[1] SIPS IN – Sustainable Intensification Production Systems for Improved Nutrition, a part of the Sustainable Intensification Innovation Lab (SIIL) through the Feed the Future program financed by USAID. IWMI, Bahir Dar University and Kansas State University are some of the partners. https://www.feedthefuture.gov/feed-the-future-innovation-labs/

carried out among farmers in the two areas. The survey concluded that urea and diammonium phosphate (DAP) were the most used fertilisers within the two areas which makes nitrogen related water quality parameters of interest.

Because of the different geophysical attributes of the two watersheds (see section *2.3 Study Areas*), the runoff mechanisms may vary making the spatial location of the wells of interest. Earlier studies in the Ethiopian highlands by Moges et al. (2018) showed that saturation excess runoff is the most dominating runoff mechanism, but the flow differ depending on position in the landscape. Mogest et al. (2018) divided the landscape in three zones; the valley bottom (saturated during rainy season), the degraded hillsides which were considered to contribute to runoff and finally the hillside infiltration zone where rainwater percolates and contributes to interflow or base flow. Since the flow patterns vary in the landscape, the contamination level of wells with different position in the landscape may differ, as well as the contamination levels between the watersheds.

1.1 OBJECTIVES

The objective of this study was to investigate how agricultural intensification influences the concentration of nitrogen compounds (nitrate, nitrite and ammonia) in shallow groundwater by combining water quality data sampled from wells with survey data covering agricultural habits. To assess the objective, the study compares two watersheds, Dangishta and Robit Bata, which differ somewhat in levels of agricultural intensification and topography. Robit Bata watershed is considered to be more intensified regarding irrigation and fertilisation management than Dangishta watershed. Furthermore, Robit Bata has a more hilly topography than Dangishta.

The following questions will be examined:

- How does the concentration of nitrogen compounds in shallow groundwater vary in space and time? Are the WHO guidelines exceeded?
- Are temporal and/or spatial patterns of nitrogen found in shallow groundwater related to agricultural intensification (i.e. fertiliser usage, irrigation usage, livestock) or watershed characteristics?

2 BACKGROUND

2.1 NITROGEN

Nitrogen is an important nutrient for the productivity in ecosystems due to its crucial parts in proteins, DNA, RNA and in the chlorophyll molecule (Eriksson et al., 2011). Many agricultural production systems are nitrogen limited justifying nitrogen application to cultivation systems to increase the yields (Eriksson et al., 2011 and Galloway et al., 2004). To be useful in production systems nitrogen must be in a plant available compound. Naturally, there are three ways to transform dinitrogen (N_2) from the atmosphere into a bioavailable form, by lightning, by wildfires or by nitrogen fixation through microorganisms. In the atmosphere, the energy released by lightning can break the N_2 bond and enable a reaction with oxygen forming nitrogen oxides (NO_x). Nitrogen oxides dissolve and transform into nitrate in rain. Through biological processes microorganisms mineralise organic bound nitrogen into inorganic compounds which makes the nitrogen plant available (Eriksson et al., 2011). If the process is reversed, i.e. inorganic compounds is fixed into organic compounds, the process is called immobilisation. The largest uptake of nitrogen in crops in cultivated land is through ammonium (NH_4^+) and nitrate (NO_3^-). In addition, in systems with low nitrogen content plants can use organic bound nitrogen e.g. amino acids (Eriksson et al., 2011).

In the soil, nitrogen can transform into different compounds through oxidation and reduction. These processes are usually called the nitrogen cycle and a variety of organisms are involved as wells as external factors, for example oxygen content and pH (Eriksson et al., 2011). In aerobic conditions ammonium transforms into ammonia (NH_3) and hydrogen (H^+) according to Equation 1.

$$NH_4^+ \leftrightarrow NH_3 + H^+ \qquad (1)$$

The reaction is dependent on pH and will be shifted to the right if pH is high. The ammonia molecule can then oxidise into nitrate in a two-step procedure described in Equation 2 and Equation 3. This procedure is called nitrification (Eriksson et al., 2011).

$$2NH_3 + 3O_2 \rightarrow 2NO_2^- + H^+ + 2H_2O + energy \qquad (2)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- + energy \qquad (3)$$

Nitrification is performed by microorganisms in the soil that use the released energy from the process to the assimilation of carbon dioxide and sodium bicarbonate. Nitrite (NO_2^-), the product of Equation 2, usually oxidise into nitrate short after creation making accumulation in the soil rare. The reverse process, presented in equation 4, is called denitrification and is performed by bacteria or archea during anaerobic conditions. The absent of oxygen makes the usage of nitrate as an electron acceptor for oxidisation of organic material or sulphur the drive behind the process.

$$2NO_3^- \rightarrow 2NO_2^- \rightarrow 2NO\uparrow \rightarrow N_2\uparrow \qquad (4)$$

The proportions between the nitrogen compounds in the denitrification process depend on the availability of nitrate and oxygen, pH, temperature and bacteria species. (Eriksson et al., 2011).

2.1.1 Leaching of nitrogen

If too much nitrogen is added to a system, leaching becomes a risk. Leaching of anthropogenic nutrients, particularly nitrogen and phosphorus, can cause eutrophication and result in water bodies with hypoxia (Conley et al., 2009). In nature, nitrate is generally a mobile ion since its negative charge prevents it to bound to soil particles that usually is negatively charged as well. Therefore, leaching becomes a risk if the nitrate concentration is high, which can be caused by either fertilisation or a high rate of nitrification (Eriksson et al., 2011). However, in soils with high content of the positively charged iron oxide, leaching is usually smaller since adsorption of the negatively charged nitrate ion is possible. If particles in soil are negatively charged, ammonium usually does not leach because the positively charged ammonium ion is bonding to these particles. Ammonium in soil is usually transformed into nitrate through the nitrification process which makes the leaching of ammonium even less common, Equation 1 to 3. (Eriksson et al., 2011).

Because of the mobility of nitrate, this is the most common nitrogen compound found in ground water. The nitrite ion will potentially also leach, but the since it is the intermediate product of nitrification as well as denitrification, it is relatively unstable and will be found in less extent, see Equation 2 to 4 (Burkart and Stoner, 2001). In anaerobic conditions nitrate is used in the denitrification process (Equation 4) and studies have shown that the concentration of nitrate in saturated zones decline with depth below the water table (Geyer et al., 1992). As described above, the leaching of ammonium in soils is rare and in solution, the ammonium ion will be in equilibrium with ammonia, Equation 5. The equilibrium is pH dependent and the concentration of ammonia will increase when pH increase (Anthonisen et al., 1976).

$$NH_4^+ + OH^- \leftrightarrow NH_3(aq) + H_2O \qquad (5)$$

An extensive leaching of nitrogen into water bodies used as drinking water can be harmful to humans if the concentrations of the compounds become too high. The World Health Organization (WHO) has established guidelines for nitrate and nitrite concentration in drinking water. WHO's guideline for nitrate concentration in drinking waters is maximum 50 mg l^{-1} which is equivalent to 11.3 mg l^{-1} as nitrate- N. The recommended value of 50 mg l^{-1} is set to be protective for bottled-fed infants and is based on the result of epidemiological studies. The maximum value for nitrite is 3 mg l^{-1} which is equivalent to 0.91 mg l^{-1} as nitrite -N (WHO, 2017). According to WHO (2017) nitrite is more toxic than nitrate and has also been linked to methemoglobinemia among bottle-fed infants. There is no established guideline value for ammonia in drinking water since it is considered to occur in concentrations that are non-harmful for humans (WHO, 2017).

2.1.2 Fertilisers used in Ethiopia

Fertilisers are used in food production systems to add nutrients to the crops and consequently increase the productivity. In 1913 the Haber-Bosch process was developed which made it possible to produce ammonia out of nitrogen gas and hydrogen gas. This development was of great importance for the modern agriculture since ammonia is a compound in many fertilisers (Galloway et al., 2004).

Urea, $CO(NH_2)_2$, is produced out of carbon dioxide and anhydrous ammonia during high temperatures and pressure (Glibert et al., 2006). Urea contains about 46% of nitrogen (Finch and Samuel, 2002). When applied in agriculture, it is transformed to ammonia (NH_3) or ammonium (NH_4^+) by microorganism, Equation 6.

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2 \quad (6)$$

The reaction results in a higher pH and an accumulation of ammonium, see Equation 1 (Bremner, 1995).

Diammonium phosphate, DAP, consists of two ammonium ions and one phosphate ion. The usage of DAP reaches back until the 1960s and is produced with a reaction of phosphoric acid and ammonia. The nitrogen content in DAP is about 18%. The DAP molecule dissolves in soil into plant available ammonium and phosphate ions (International Plant Nutrition Institute, n.d.). Following Equations 1 to 3, the ammonium ions will be converted into nitrate.

Sub-Saharan Africa is facing a dilemma described by Masso et al. (2017) as the “too little and too much” paradox. In short, too little nitrogen is being used to secure food production but on the other hand too much is being used causing nitrogen load to waterbodies (Masso et al., 2017). In Ethiopia, a mean nitrogen usage of 10.4 kg ha^{-1} have been reported from 2010 FAOSTAT data whereas data from 2011-2012 established the mean nitrogen use to 23.0 kg ha^{-1} (Sheahan and Barrett, 2017). Data from year 2000 stated a nitrogen depletion of 47 kg ha^{-1} $year^{-1}$ (Chianu et al., 2012). In comparison, the nitrogen fertiliser input in Danish agriculture is 45 kg ha^{-1} and the surplus of gross nitrogen balance is 80 kg ha^{-1} $year^{-1}$ (Hellsten et al., 2017).

2.1.3 Livestock and nitrogen

Livestock influences the nitrogen cycle through their manure. The nitrogen content in the manure varies with type of animal, feed composition, productivity and management (Hou et al., 2016). Direct deposits of manure on fields return some of the nitrogen to the system but parts of it leave through gas emission. In addition, leaching and erosion can contribute to the loss of nitrogen (Steinfeld and Wassenaar, 2007). A study from the Ethiopian highlands evaluating nutrient compounds from small scale farms and an experimental station concluded that the nitrogen content in cattle manure varied between 11.7 - 27.4 g kg^{-1} dry weight manure with a mean of 18.3 g kg^{-1} (Lupwayi et al., 2000). In Dangishta and Robit Bata watersheds (Figure 2), cattle are the dominated livestock followed by mule and sheep.

2.2 HILLSLOPE HYDROLOGY PROCESSES

Precipitation falling over a watershed is either stored or turned into evaporation or runoff. *Surface runoff* occurs on the ground surface if the infiltration rate of the soil is exceeded by the intensity of the precipitation or if the soil is saturated to its full capacity (Grip and Rodhe, 2000). *Subsurface flow* is water that infiltrates the soil and then empties into a stream channel. Also included in the concept of runoff is groundwater discharging into a stream (The Editors of Encyclopaedia Britannica, 2017).

The direction of the groundwater flow depends on the hydraulic head (total head) and flows from high to low head. The hydraulic head is the total pressure from a liquid above a datum and consists of the pressure head above the measuring point and the elevation head (Domenico and Schwartz, 1998). Generally, groundwater movement on landscape scale follows the topography and topographic dividers also divide the direction of the groundwater, which is driven by the gravitational force, Figure 1. Elevated areas of landscape usually are recharge areas whereas lowlands usually are discharge areas. This is explained by the fact that the hydraulic head typically decrease with elevation and soil depth in highlands whereas it is the opposite for lowlands (Domenico and Schwartz, 1998). This simplified view is mainly valid for saturated groundwater flow in homogeneous and isotropic soils since factors such as different hydraulic conductivities, impermeable layers and fractions can influence the flow pattern.

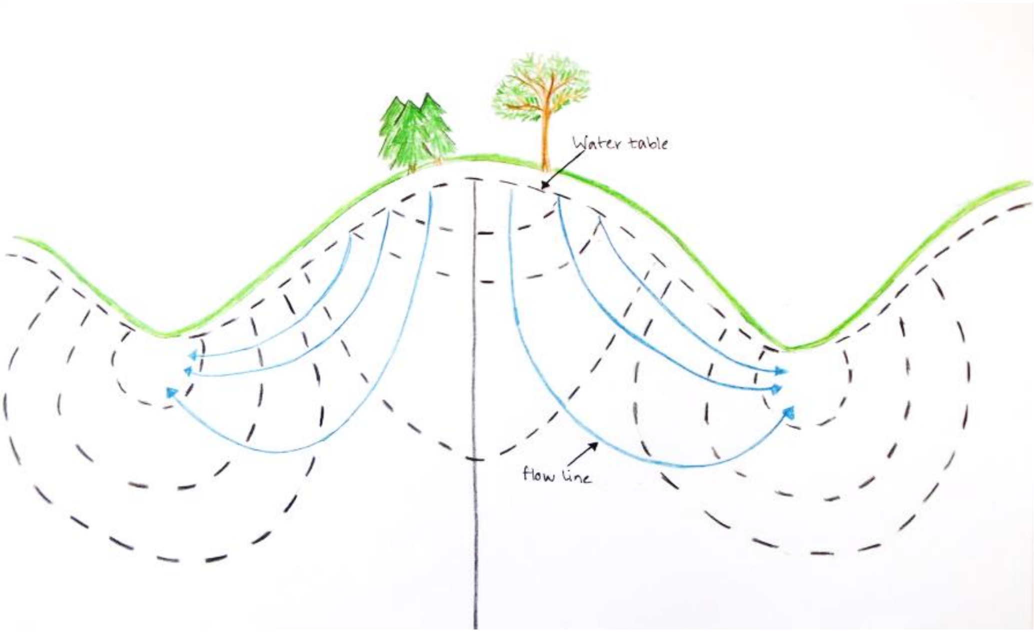


Figure 1. Flow pattern controlled by topography. The dashed lines are the equipotential lines whereas the blue arrows show the flow direction of water. The black vertical line marks the topographic divider. Inspired by original of Hubbert, M (1940). Theory of Groundwater Motion. Journal of Geology, 48, 785-944.

The flow direction in unsaturated hillslopes are a bit more complex than saturated groundwater flow. In addition to water, air in the pores also becomes a factor and correspondingly the suction head gradient becomes important. The suction head, sometimes referred to as tension head, is the state at which the pressure head is less than the atmospheric pressure. Consequently, in an unsaturated soil there will be no flow into a borehole since the pressure head in the hole is higher than in the soil water (Domenico and Schwartz, 1998).

Soil characteristics, particularly water permeability and occurrence of restrictive layers determine the flow in hillside areas. Water permeability is a measure that indicates the capacity of water to pass through a material, often expressed by the permeability coefficient or hydraulic conductivity in m s^{-1}. Water percolates downward in the soil matrix until it reaches a restrictive layer or groundwater table. Restrictive layer at shallow depths will cause subsurface lateral flow driven by a force equal to the slope while restrictive layers deeper down will permit water to percolate until it reaches the water table and then flow as base flow (Rittenburg et al., 2015). Bedrock or increased clay content/ bulk density are example of subsurface restrictive layers (Rittenburg et al., 2015). Therefore, to determine the exact groundwater flow knowing the pedological and geological stratification is of importance (Domenico and Schwartz, 1998).

A study covering three different areas in the Amhara Region in the Ethiopian Highlands by Engda et al. (2011), showed that the infiltration rates in general were higher than the rainfall rates. The study concluded that precipitation infiltrated the soil in the steeper part of the watershed and flowed downward as lateral subsurface flow while surface runoff could be generated from saturated areas, usually at the lower flatter part, and from uncovered bedrock (Engda et al., 2011). Another study from a watershed in the Amhara Region showed that the infiltration capacity of the soil in general were greatest in upslope areas and smallest in down slope positions and the runoff mechanism was dominated by saturation excess (Tilahun et al., 2016). In Robit Bata watershed a study estimating potential groundwater storage in hillside aquifers used a conceptual model to describe the hydrological processes. The lateral subsurface flow was dominant and little surface runoff occurred due to a permeable root zone as top layer (Tilahun et al., in prep.). The hydrological behaviour in the rain season was described as a dynamic process where water percolates downward until the soil reaches field capacity and, if rain continues, resulting in a rising water table in the unsaturated zone. If the recharge is greater than the lateral flow the ground water table continues to rise. When rainfall decrease, the lateral flow become dominant and the water table level decreases (Tilahun et al., in prep.). Consequently, spatial and seasonal variation in runoff processes within the watersheds are expected.

2.3 STUDY AREAS

Both study areas in this project, Dangishta and Robit Bata, are watersheds situated near the city of Bahir Dar in the adjacent of Lake Tana in the north-western part of Ethiopia, (Figure 2). The climate is considered as moist subtropical and is divided in dry and rain period. The dry period usually reaches from October until April while the rain period stretches from April until September (National Meteorology Agency, n.d.) The agriculture conducted in the watersheds is dominated by traditional methods with small scale irrigation during the dry period. The main fertilisers used in the watersheds are urea, DAP and compost (Water Abstraction Survey, 2017). Livestock in the watersheds is usually free grazing during day but tied up at night. However, tied up livestock occurs during day as well.

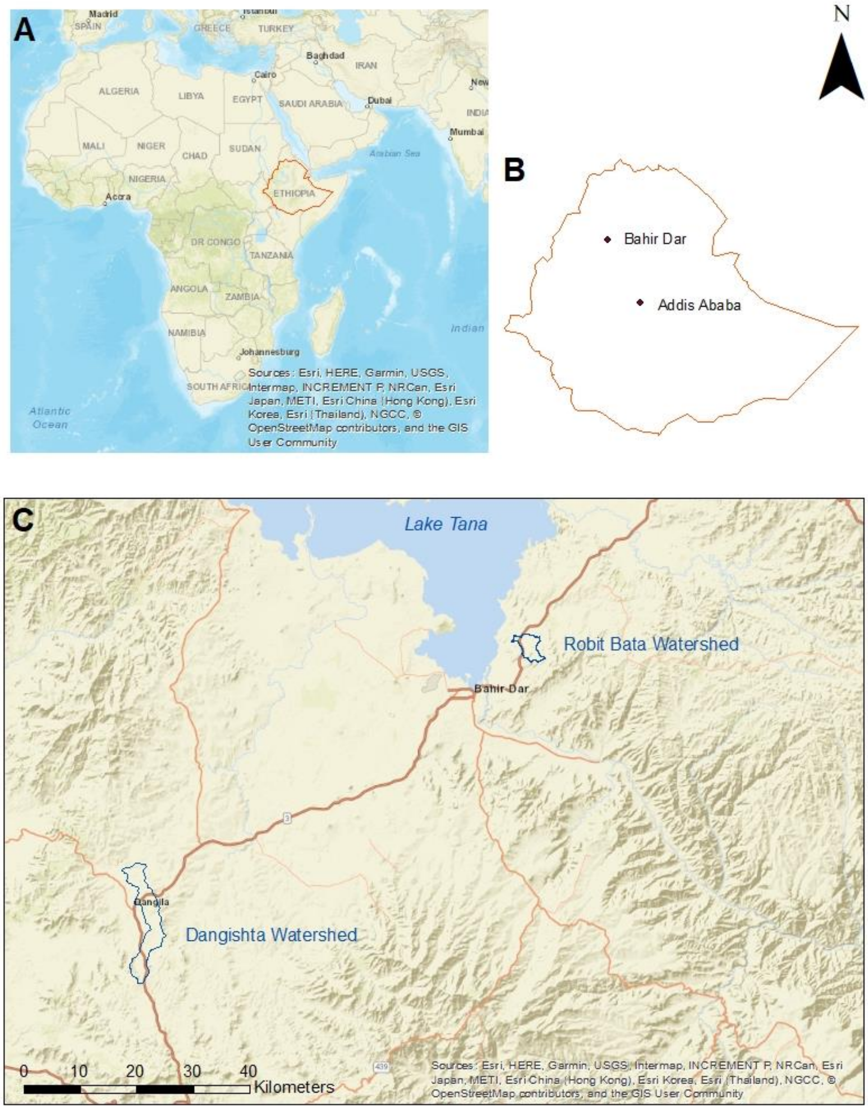


Figure 2. A) The location of Ethiopia on the Horn of Africa. B) The city of Bahir Dar in north western Ethiopia. C) The Dangishta and Robit Bata watersheds near Bahir Dar and Lake Tana.

2.3.1 Dangishta Watershed

The Dangishta watershed is situated near the town Dangila, around 70 km southwest from Bahir Dar (Figure 2). The watershed covers an area around 5700 ha and consist of low hills and floodplains, Figure 4. The floodplains are mainly used as pasture for livestock whereas the slopes are dominated by crops and homesteads (Walker et al., 2016). The agriculture in the area is mostly rainfed but irrigation occurs on small home garden plots. (Walker et al., 2016). The most used water abstraction techniques for irrigation are rope and washer pumps, closely followed by rope and pulley, Figure 3 (Water Abstraction Survey, 2017). The main crop production in the area take place during the rainy season where cereals such as teff, maize and millet are cultivated (Atinkut, 2015). The crops irrigated during the dry season are vegetables such as tomato, garlic and pepper and shrubs as coffee and gesho[2].

A

B

Figure 3. A) The rope and washer pump technique. B): The pulley and bucket water abstraction technique (Larsson, 2018).

During the 10 years period between 2008-2017 the annual mean precipitation was 1767 mm. In mean, about 87% of the precipitation fell between May and the end of September during this period (NMA, 2018). In 2017 the rainfall was 2025 mm. The median annual daily maximum and minimum temperature measured at the National Meteorology Agency's station in Dangila is 25 °C and 9 °C respectively (Walker et al., 2016).

[2]African shrub. Used in Ethiopia to make the traditional drinks tella and tej

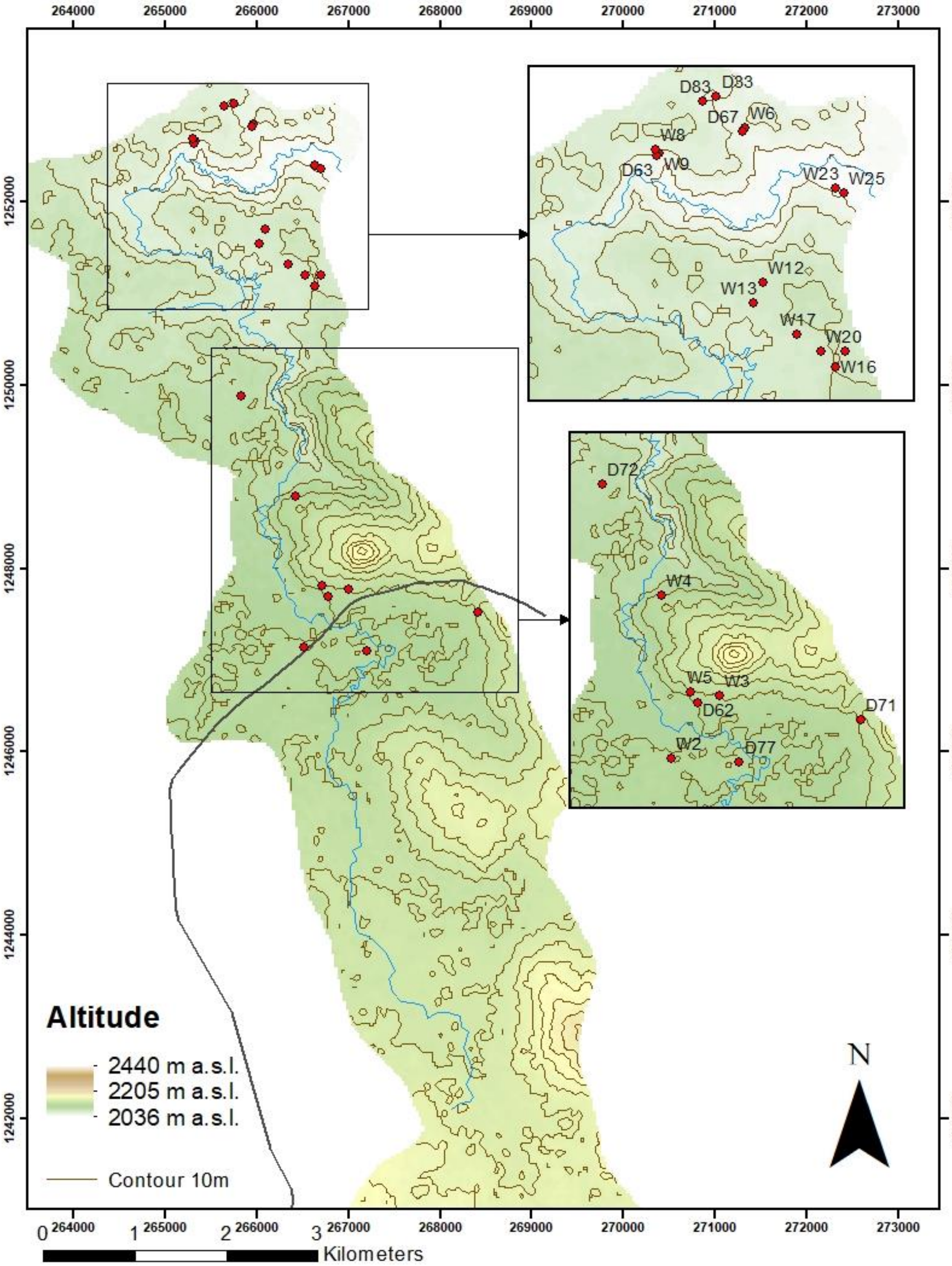


Figure 4. An overview of the Dangihsta watershed with wells used in the study marked with red dots.

2.3.2 Robit Bata Watershed

The Robit Bata Watershed is situated around 15 km north of the central parts of Bahir Dar (Figure 2). The watershed is 1412 ha with an elevation varying between 1800 to 2029 m a.s.l. and a stream with outlet in Lake Tana runs through the watershed. The watershed is characterized by floodplains downstream and steep topography upstream, Figure 5 (Walker, 2015). About 85 % of the precipitation falls between June and September and the total yearly amount of rainfall sums up to 1450 mm (Tilahun et al., in prep.). In 2017 the yearly rainfall was 1560 mm.

Agricultural land use covers around 80% of the watershed area. Mainly cereal crops are cultivated in the rainy season whereas small plots of cash crops, such as vegetables or khat, are irrigated during the dry season (Tilahun et al., in prep.) The water abstraction technique used for irrigation is, for most of the households, the pulley and bucket technique whereas a small part of the households uses a fuel driven pump (Water Abstraction survey, 2017). The small-scale irrigation in the watershed has expanded over the latest years resulting in a fluctuation of water levels in the wells over the year and the river drying up during the dry season (Tilahun et al., in prep.). A study about irrigation potential in Robit Bata showed that the water table is about 3-5 m from the ground surface in August but in the end of the dry season it can reach as low as around 11 m at some places (Tilahun et al., in prep.).

Generally, the Robit Bata watershed is considered more intensified regarding usage of fertilisers and irrigation than Dangishta watershed. Robit Bata has also steeper slopes compared to Dangishta.

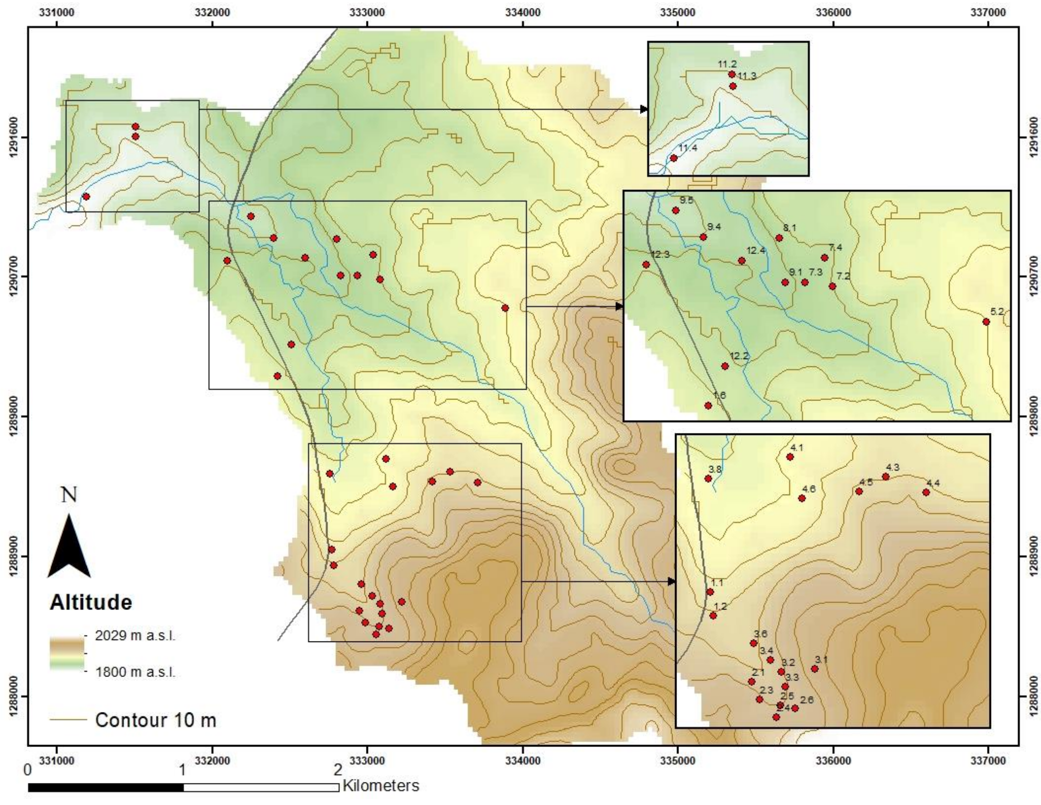


Figure 5. Overview of the Robit Bata watershed with wells used in the study marked with red dots.

3 DATA

3.1 WATER QUALITY DATA (SIPSIN)

The water quality data used in this project was monthly sampled and covers the year of 2017. The data is an extraction of an ongoing Sustainable Intensification Innovation Lab project called SIPS-IN[3](named SIPSIN in the following), which is a collaboration between IWMI, Bahir Dar University and several other actors financed by USAID through their program Feed the Future. In field, water samples from both watersheds were collected in plastic bottles by local data collectors in the beginning of every month during 2017 from all wells in Figure 4 and Figure 5. The samples were transported to Bahir Dar University for laboratory analyses. The water quality parameters used in this study (nitrate, nitrite and ammonia) were analysed by employees at University of Bahir Dar using ELE Paqualab Photometer 430-550 from ELE International. The devise is a colorimeter which is built on the principle that the concentration of a solute is proportional to the absorbance. The ELE Paqualab Photometer measure the transmittance (%T) that passes through a sample at a specific wavelength which can be translated into concentration for a specific solute. By using a blank sample with transmittance of 100% the photometer is calibrated before each analysis (ELE international, n.d). The concentration of the nitrogen parameters was presented in the units of nitrate-nitrogen, nitrite-nitrogen and ammonia-nitrogen mg l^{-1}. The measurement ranges for nitrate, nitrite and ammonia are 0-20 mg l^{-1} NO_3^--N, 0-0.5 mg l^{-1} NO_2^--N and 0-1.0 mg l^{-1} NH_3-N respectively. If the measurement range were exceeded the samples were diluted. In charge of the analyses was PhD student Feleke Kumraz at Bahir Dar University.

The SIPSIN project covers 32 and 33 wells from Dangishta and Robit Bata respectively. In addition to the water quality parameters, geospatial information of the sampling locations was also provided. In this study 23 wells from Dangishta and 33 wells from Robit Bata are used, Figure 4 and Figure 5. Information about water levels in the wells can be found in Appendix A.

3.2 WATER ABSTRACTION SURVEY (WAS)

In the end of 2017, a survey was carried out among farmers in the Robit Bata and Dangishta watersheds as a part of the ILLSI-project to evaluate water abstraction, irrigation habits, holding of animals and use of fertilisers and pesticides. Various enumerators were used to interview farmers in the watersheds and the enumerators also collected geospatial information of households and wells using GPS devices. The farmers were interviewed in Amharic, the langue spoken in the region, and the answers where translated into English when digitalised. In charge of compiling the survey was Teshager Assefa at Bahir Dar University. In Dangishta watershed 62 farmers were interviewed and for Robit Bata watershed the corresponding number was 89. In the remainder of this report the water abstraction survey is referred to as WAS.

[3] Sustainable Intensification Production Systems for Improved Nutrition. https://www.feedthefuture.gov/feed-the-future-innovation-labs/

3.3 WEATHER DATA

Daily rainfall data from the National Meteorology Agency in Ethiopia was used to evaluate the influence from rainfall events. For Dangishta, data was collected from a station in the city of Dangila, around 2 km from the middle of the watershed and for Robit Bata, data from the Bahir Dar station around 20 km away from the watershed was used, Appendix B.

4 METHODS

This chapter covers the methods used in the project. In general, the idea behind this paper was to link the WAS from 2017 to SIPSIN data from the same year and evaluate if the levels of contamination in the wells could be explained by spatial or temporal factors. In short terms the procedure included three steps:

1. Preparing and matching the data from WAS and SIPSIN
2. Examine flow patterns of the groundwater in the watersheds to determine if flows from upstream locations to downstream wells were possible
3. Conduct analyses and statistical tests

4.1 PREPARING THE DATA

4.1.1 Geospatial information

Farmers who occurred in both the SIPSIN data and WAS were identified by comparison of names. Geospatial information of the wells from SIPSIN and WAS for overlapping farmers were imported into the software ArcMap to check for consistent geospatial references. In case of inconsistency in position, a cross checking was done by comparing the positions of the well with geospatial information of the household given in WAS. The overlapping wells of the SIPSIN and WAS are further on called SIPSIN-WAS wells, Figure 6.

Two field visits to each of the watersheds were done during September and October 2018. The purpose of the first visit was to get an overview of watershed characteristics and the purpose of the second visit was to control geospatial positions and information about fertilisers, water abstraction and irrigation given in WAS. The field visits were done together with Master students from Bahir Dar University also working with projects within respectively watershed. The Master students helped with interpretation when talking to the farmers and a local data collector guided to the households. Not all overlapping wells in the watersheds were visited due to farmers being away from home when arriving at the household and the time-consuming large distances that had to be covered by foot. After the field visits inconsistency in position still occurred for some wells and the position for these were later validated in field by a PhD student doing research in the watersheds.

In the nearby area of Dangishta, WAS consisted of 62 households. 23 of households were removed due to position outside the experimental watershed, leaving 37 households left in the survey. From the total number of 32 wells in the SIPSIN water quality data, 23 were located inside the experimental watershed and used in the analysis. 13 farmers had both a well in the SIPSIN data and existed in WAS. In addition, two individuals were assigned ownership for two wells each, making the number of wells to 15. The households from the WAS are named ID followed by a number and the wells from the SIPSIN data are shortened W or D followed by a number (e.g. ID135, W25 and D63).

WAS of Robit Bata consisted of 88 households. 28 households were removed due to position outside the experimental watershed, leaving 60 households left from the survey. From the total number of 33 wells in SIPSIN data 23 of them were overlapping with WAS. The households from the WAS are called ID followed by a number and the wells from the SIPSIN data are shortened by a number (e.g. ID74 and 2.2).

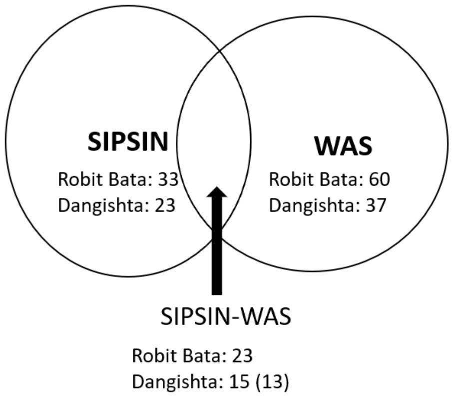


Figure 6. A Venn diagram showing the overlapping data (SIPSIN-WAS) from the water quality data (SIPSIN) and the water abstraction survey (WAS).

4.1.2 SIPSIN-data

Several values in the SIPSIN data for Dangishta and Robit Bata were marked with “nd” (no detection) indicating that no concentrations of the nitrogen compounds where detected in the analysis. The measurement range by the ELE Paqualab Photometer 430-550 started at zero for each of the nitrogen compounds, however the actual concentration being zero may not be true. The lowest non-zero value that ELE Paqualab Photometer 430-550 could detected is 0.03 (94% T) for nitrate, 0.001 (98% T) for nitrite and 0.01 (82% T) for ammonia. The “nd” values were assigned with half of these concentrations (0.015, 0.0005 and 0.005 respectively).

For Dangishta the number of “nd” values for nitrite and ammonia was six and 86 respectively whereas the number of “nd” values for Robit Bata were five, five and 93 for nitrate, nitrite and ammonia respectively. All “nd” values were assigned with their corresponding values mentioned above.

4.1.3 Water Abstraction Survey (WAS)

Information about the monthly usage of fertilisers applied on farmers’ fields, was extracted and transformed into total amount of N-fertiliser for each farmer by using nitrogen content factors given in literature. Urea, DAP and compost were multiplied with their corresponding dry weight factors of 0.46, 0.18 and 0.0183 (see section *2.1.2 Fertilisers used in Ethiopia* and *2.1.3 Livestock and nitrogen*). The value for compost was considered to correspond to the nitrogen content of 18.3 g kg^{-1} for cattle manure given by Lupwayi et al. (2000) (*2.1.3 Livestock and nitrogen*). The nitrogen content values used were based on dry weight since it was considered that only manure free from urine was applied on the fields of the farmers.

The data regarding the farmers irrigation water use and practised habits was evaluated and when contradictory information was given at different parts in WAS, the most likely value was selected. If suitable information from the field visits were available, these were used. In WAS, information about irrigated area, how often irrigation occurred, and the number and volumes of buckets used at each irrigation were given, making it possible to calculate the amount of water used for irrigation. However, one or more of those parameters were often missing, resulting in that the amount of water used for irrigation only could be calculated for a small portion of the households.

The holding of animals in WAS was specified by number of each species. Oxen, dairy cows, heifer and calves were presented in different categories but were summed up using the name cattle. The animals were converted into Tropical Livestock Units (TLU). TLU is an equivalent of livestock biomass where one TLU is equivalent to 250 kg, representing one ox (Robinson et al., 2011). The following conversion factors were used: horse 0.8, cattle and mules 0.7, donkey 0.5 and sheep 0.15 (Rimhanen and Kahiluoto, 2014). The potential nitrogen extraction from manure per each household was calculated by multiplying each TLU category with corresponding monthly manure production and specific nitrogen content. The nitrogen content was set to 0.0183 for cattle and 0.038 for the others (Lupwayi et al., 2000 and FAO, 2011). The manure production rates used were 3.3 kg day^{-1} TLU^{-1} for cattle and 2.4 kg day^{-1} TLU^{-1} for equines (Haileslassie et al., 2005). The manure production rate used for sheep was 0.41 kg day^{-1} TLU^{-1} (Gbenou et al., 2017).

4.1.4 Rain data

The rain data were marked with tr (trace of rain) 8 times for Dangishta and 3 times for Robit Bata, in the cases that the amount of rain was less than the measurable limit, that usually is 0.05 mm rain. These days were assigned with zero since it was considered that the values would not influence the results. When crosschecking by assigning 0.05 instead of zero, the greatest difference would occur in March for Dangishta watershed adding 1 mm to the total monthly sum, which was considered negligible. The daily rain data was summed, between each water sampling occasion, to monthly sum for use in statistical tests.

4.2 FLOW PATTERNS AND DRAINAGE AREA IN ARCMAP

To determine the flow patterns in the two watersheds the software ArcMap was used. It was assumed that the subsurface flow followed the topography given the theory stated by Tilahun et al. (in prep.) described in section 2.2 in this paper. In general, there were no bedrock outcrops in the watersheds, except close to riverbanks, influencing the flow characteristics. (Walker, 2015).

A digital elevation model (DEM) over each watershed with resolution of 30.7 *30.7 m for Dangishta and 30.5*30.5 for Robit Bata were used. The *Flow direction* tool in the spatial analyst toolbox was applied to each DEM. The flow direction tool uses DEM as input and by assigning a value to each cell in a raster, based on the elevation given in the DEM, the flow direction is calculated. The cells in the output raster can be assigned with eight different values representing flow in the possible eight different flow directions (i.e. north, north east, east, south east, south etc.) that occur for each cell. A cell is given the value representing the direction of the steepest drop assuming the gravitational forces would drive the flow in that direction. Important to point out was that the DEM first was treated with the tool *Sink* before applying the flow direction set up for eliminating the chance of the flow to stop due to a sinking cell occurring in raster. Using the Sink tool will not influence the result since, in real world situations, the flow will continue after filling up the sink. The output raster from the flow direction run was, together with the locations of the wells as a weighted raster file, used as input for the *Flow accumulation* tool to visualise the drainage direction for each well.

The drainage area to each well were determined in ArcMap by converting the positions of the wells to pour points. Together with the flow direction raster, the pour points were used in the *Watershed* tool to determine the area draining to each well. The principle is as described above, all raster cells with higher elevation than the pour point will flow in that direction and will be marked as drainage area. If all neighbouring raster cells is lower than the pour point, it will result in a minimum drainage area of 943 m^2 for Dangishta and 930 m^2 for Robit Bata. The result was used to couple other wells and households within the drainage area to the specific wells.

4.3 EVALUATION AND ANALYSES OF DATA

All plots and statistical test were done in the open source programming language R using the graphical user interface Rstudio. The data was not normal distributed resulting in measures such as median and non-parametric test being used.

For both watersheds, box plots of N-fertiliser grouped by month of application were made for comparison with box plots of nitrate concentration grouped by sampling month. The non-parametric Kendall´s tau test was used to statistically evaluate if correlation between nitrate concentration, amount of applied N-fertiliser and rain fall occurred. Wells with upstream contributing areas covering additional households in WAS were adjusted for this by adding information from these households as well, before performing the statistical tests. Box plots of nitrate concentration grouped by well ID were also made to evaluate possible differences between the wells. For graphically identification of possible relationship between nitrogen load, rainfall and nitrate concentration on well basis plots with these parameters were made.

The non-parametric paired Wilcoxon signed rank test were performed on the SIPSIN-WAS wells to statistically determine if the nitrate concentration differed between the months or not. The Wilcoxon signed rank test was used since the data, grouped by month and by well, was not normal distributed even if transformed with log(x+1). In some cases, an exact p-value could not be computed due to ties or zeros. However, this did not influence if the null hypothesis was rejected which was concluded after manual evaluations.

Nitrite concentration and ammonia concentration were presented in box plots. No further analysis was performed on nitrite since there were no large variation in the data and it did not exceed the WHO guidelines. For ammonia there were several “no detection” values and no further analysis were done.

5 RESULTS

5.1 FLOW PATTERNS AND DRAINAGE AREAS

The result of the flow pattern analysis from Dangishta watershed can been seen in Figure 7. The map in the figure shows that none of the SIPSIN- wells were positioned in the direct drainage path of another well.

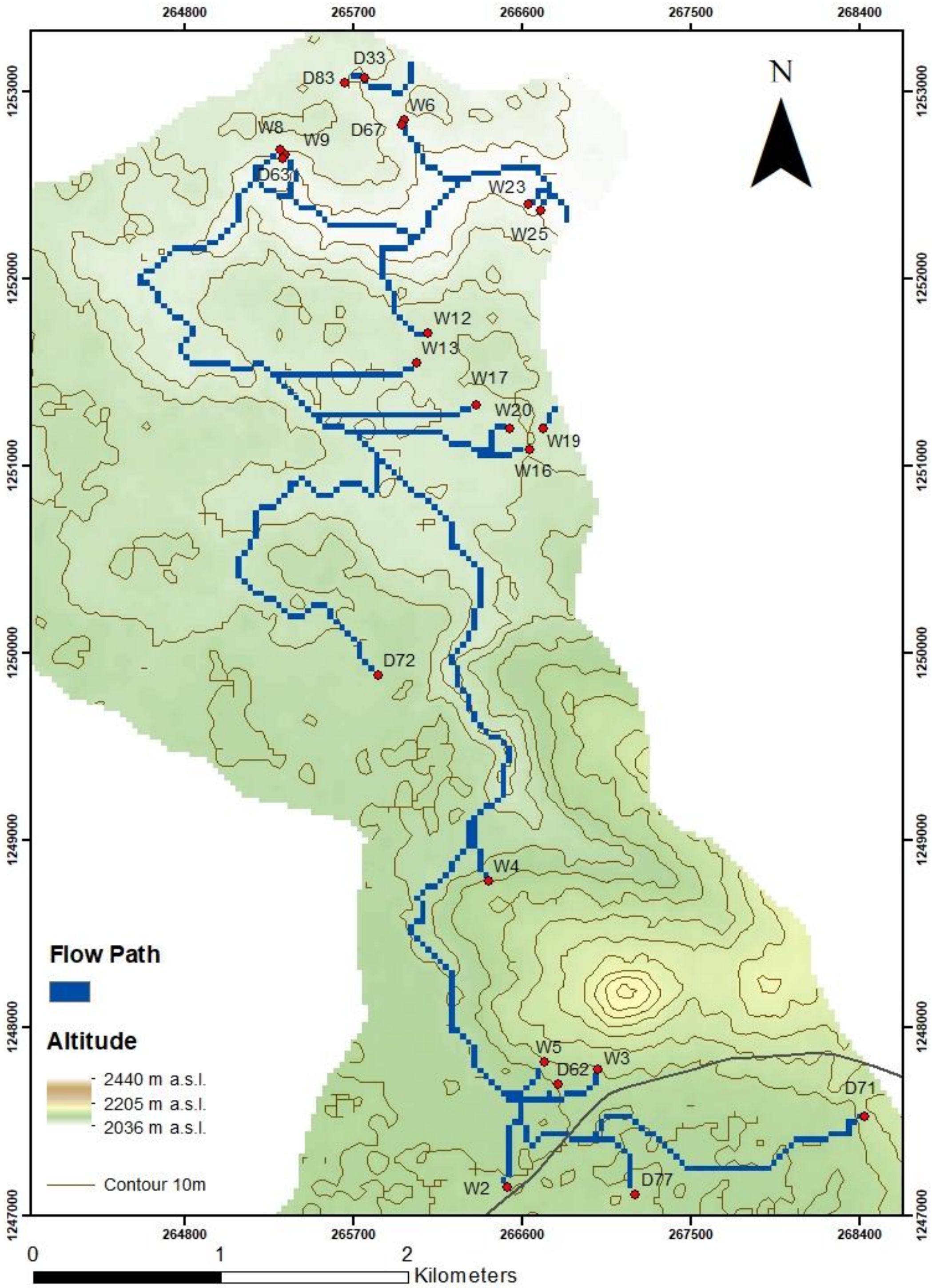


Figure 7. Map of flow pattern from the SIPSIN wells in Dangishta watershed assuming the flow pattern follows the topography.

The drainage area for each well in Dangishta watershed can been seen in Figure 8. The drainage areas were relatively small, and it was only the drainage area to well D67 that included other households from WAS than the owner of the well. According to the drainage analysis, well W9 and D63 have the same drainage area (covered in Figure 8 by the wells)

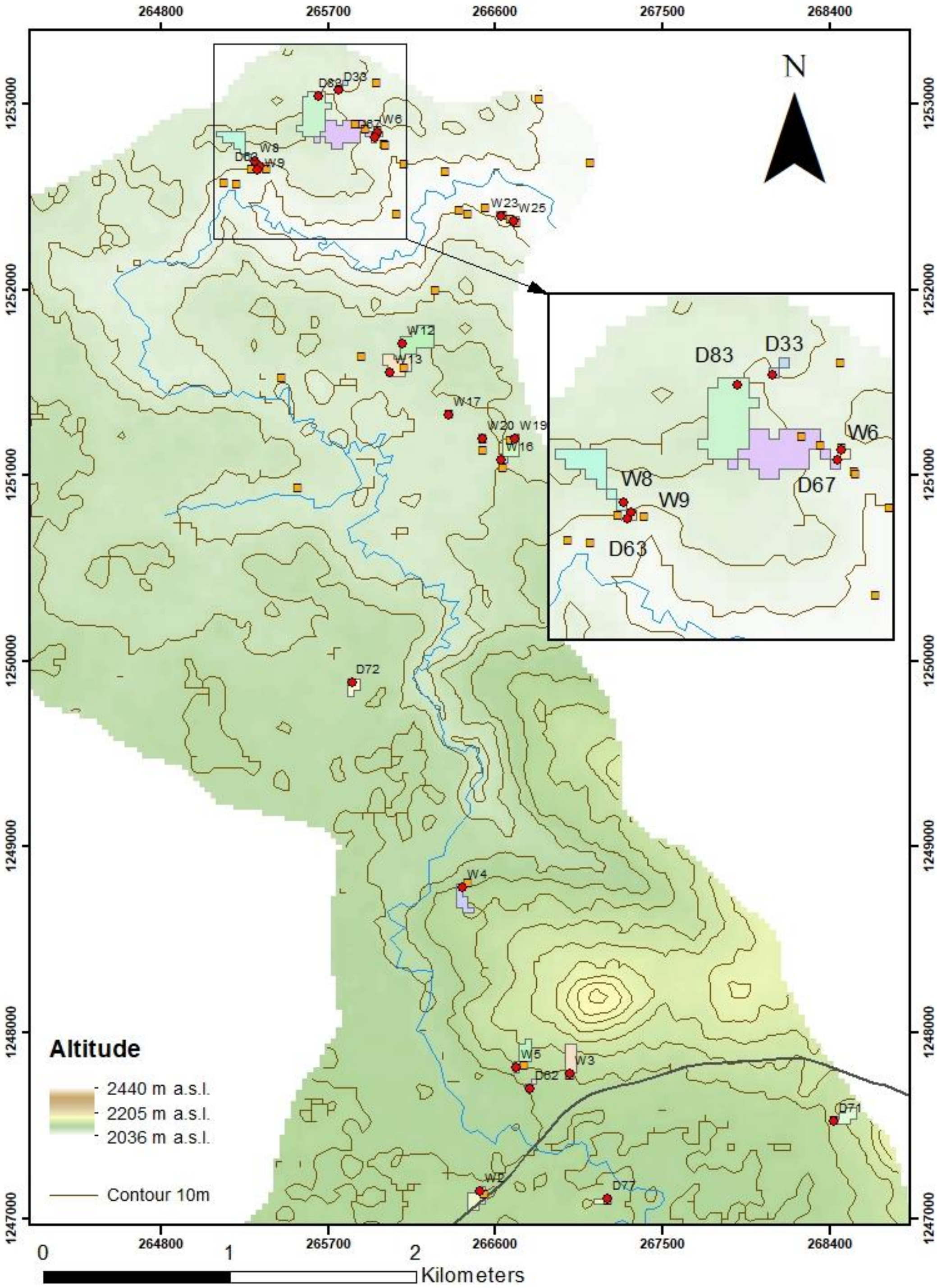


Figure 8. The drainage areas in Dangishta watershed marked with coloured shapes. The SIPSIN wells are marked with red dots and the households in WAS are marked with orange squares.

The result of the flow pattern analysis for the wells in Robit Bata watershed showed that two of the SIPSIN-wells were linked to the rest through their drainage paths, well 9.1 in the middle of the watershed and 11.4 near the outlet, Figure 9.

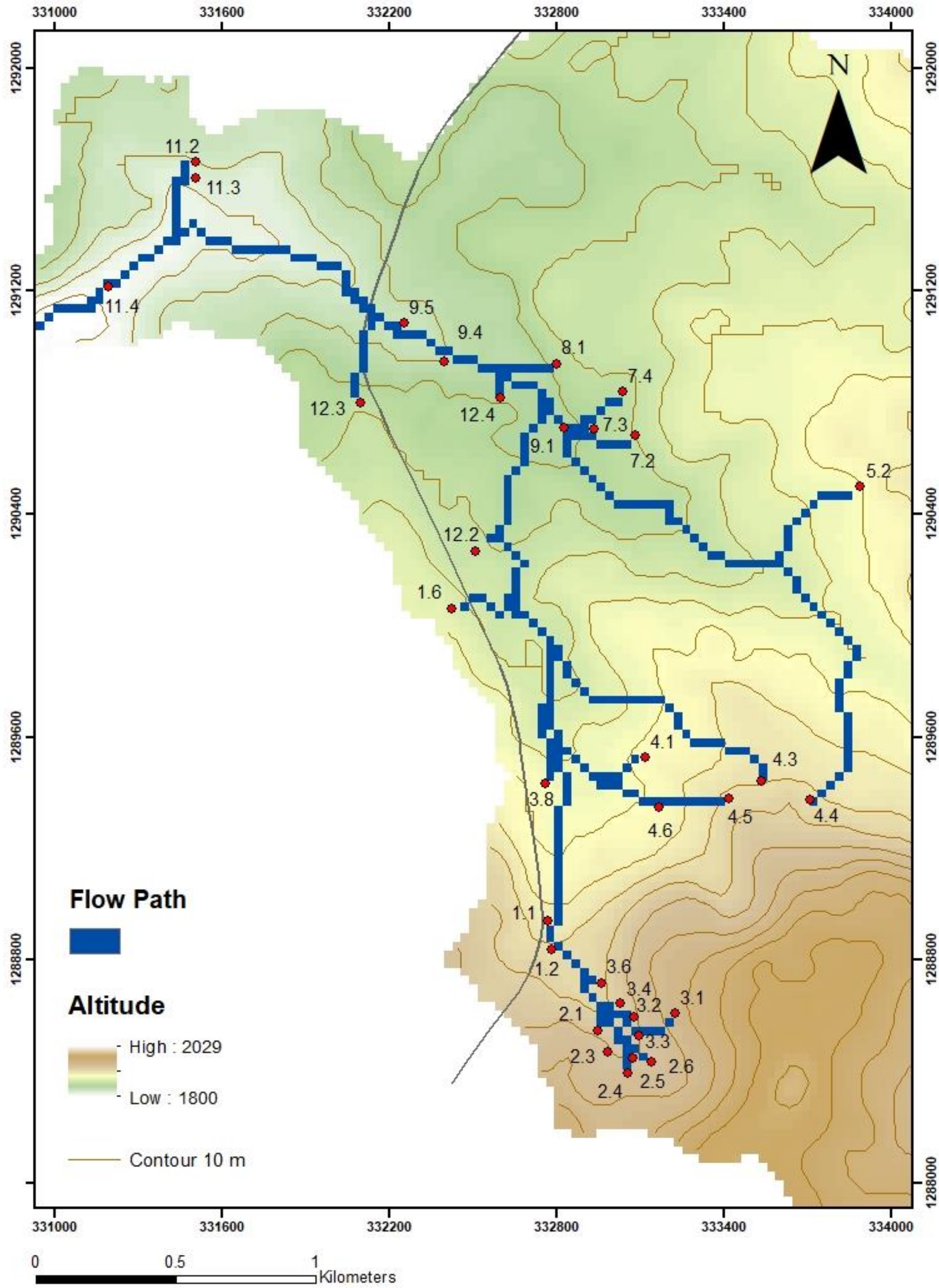


Figure 9. Map of flow pattern from the SIPSIN wells in Robit Bata watershed assuming the flow pattern follow the topography. The red dots mark the location of the wells.

The drainage area for each well in Robit Bata watershed can been seen in Figure 10. The drainage areas varied with drainage area to well 9.1 and 11.4 being the largest. Both these drainage areas included other wells and households.

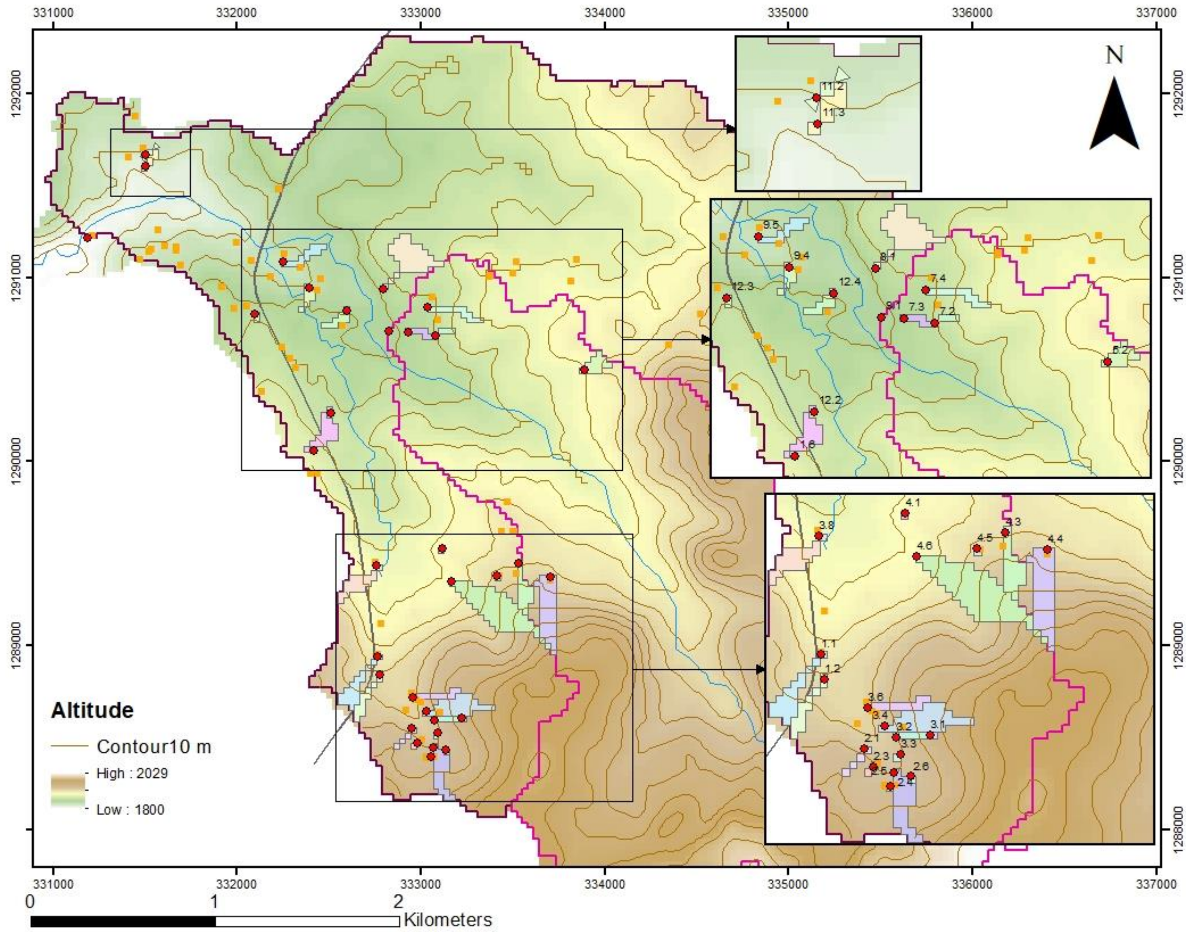


Figure 10. The drainage areas in Robit Bata watershed marked with coloured shapes and drainage areas for well 9.1 and 11.4 marked with coloured outlines (9.1 representing a large sub-watershed and 11.4 the whole watershed). The SIPSIN wells are marked with red dots and the households in WAS are marked with orange squares.

The drainage areas are for each well in Dangishta and Robit Bata watersheds are presented in Table 5 and Table 6 further down in the report.

5.2 NITRATE

The amount of nitrogen fertilisers applied on the fields in Dangishta watershed were highest in June and July which applies to both the whole watershed and when only the SIPSIN-WAS farmers were considered, Figure 11A and C. Regarding the concentration of nitrate-N, the concentrations occasionally exceeded the WHO guidelines, particularly in July and September, and the median value was highest in July both on watershed scale (n=37) and for the SIPSIN-WAS farmers (n=15). On both watershed scale and for the SIPIN-WAS farmers, the interquartile range (IQR) were greater in July and September than the months before.

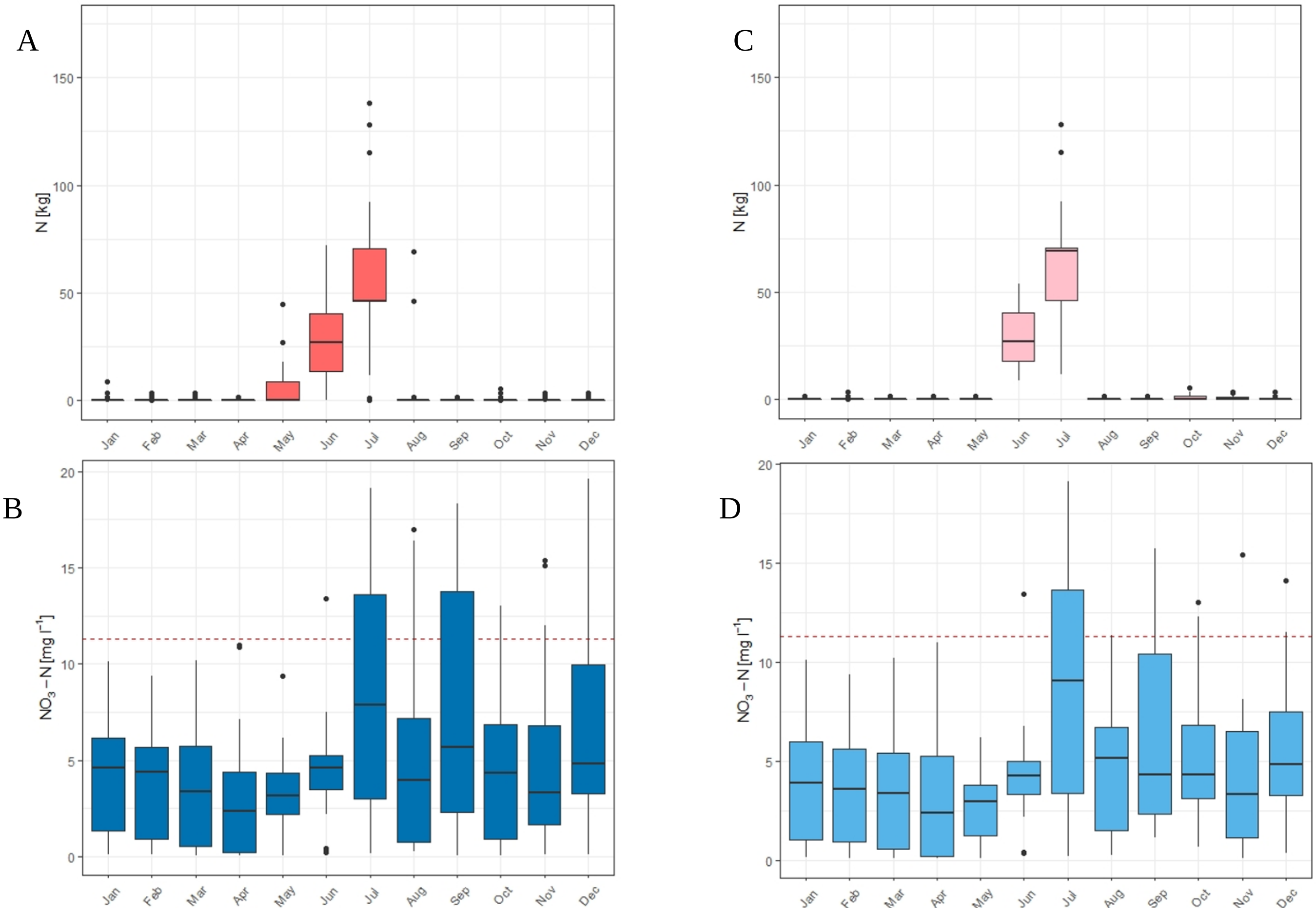


Figure 11. Box plots of the nitrogen fertilisers applied on fields and the concentration of nitrate-N in year 2017 in the Dangishta watershed. The band in the box is the median and the under quartile is the 25 % value while the upper quartile is the 75% value. The whiskers represent 1.5 IQR and the dots are samples outside that range, outliers. A) All available data for usage of N-fertiliser, n=37. B) All available data for nitrate-N concentrations, n= 23. C) Usage of N-fertiliser for SIPSIN-WAS farmers, n=15. D) Nitrate-N concentrations for the SIPSIN-WAS farmers, n=15. The dashed lines mark WHO guideline.

To evaluate if the variation in nitrate concentration significantly differed between months for Dangishta watershed, a paired Wilcoxon signed rank test was performed on the SIPIN-WAS data (n=15), Table 1. The null hypothesis was rejected for July in combination with all other months except August, September and October, indicating that the concentrations in July were significantly different ($p < 0.05$) from all months except August, September and October. The concentration in December was in addition to July also significant different from February, March, April and May. Note that the p-value for the comparison between January and February indicated that the nitrate concentration is significantly different between these months, which cannot be obviously seen in Figure 11D.

Table 1. The p-values of the Wilcoxon signed rank test performed on the SIPSIN-WAS nitrate-N data grouped by month for Dangishta watershed. The numbers in red mark when the null hypothesis was rejected, p-value < 0.05. A rejected null hypothesis indicates that the compared groups are significantly different. Values where p-value could not be computed exactly due to ties or zeros are marked with “tz”

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan												
Feb	0.010[tz]											
Mar	0.055	0.330										
Apr	0.095	0.258[tz]	0.208									
May	0.030	0.132[tz]	0.121	0.847								
Jun	0.679	0.454	0.303	0.229	0.041							
Jul	0.015	0.01	0.01	0.003	0.001	0.008						
Aug	0.934	0.639	0.277	0.107	0.064	0.303	0.055					
Sep	0.188	0.149[tz]	0.073	0.035	0.015	0.208	0.107	0.561				
Oct	0.454	0.277	0.169	0.188	0.048	0.890	0.107	0.978	0.359			
Nov	0.890	0.890	0.679	0.524	0.277	0.934	0.030	0.454	0.421	0.639		
Dec	0.095	0.045[tz]	0.007	0.015	0.008	0.208	0.048	0.421	0.851[tz]	0.847	0.359	

The amount of nitrogen fertilisers applied in Robit Bata watershed was, just like in Dangishta, highest in June and July, Figure 12. In addition, the figure shows that high nitrogen fertiliser application also occurs in August even if the median value is low. Regarding the concentration of nitrate-N, the concentrations occasionally exceeded the WHO guidelines, especially in July and November, but overall the concentration was pretty low during the entire year. In contrast to the Dangishta watershed, there was no months standing out from the rest with the nitrate-N concentration.

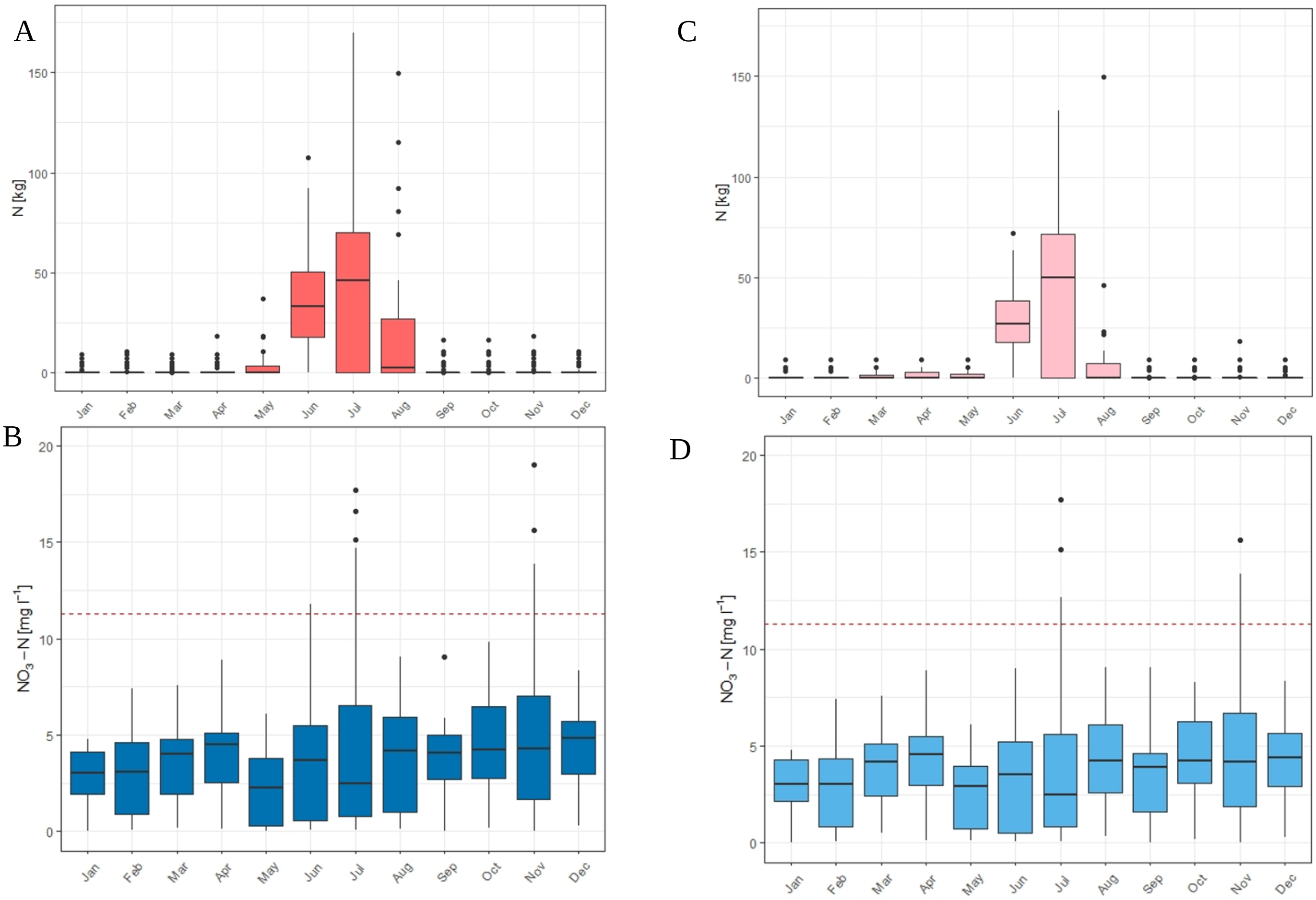


Figure 12. Box plots of the nitrogen fertilisers applied and the concentration of nitrate-N in year 2017 in the Robit Bata watershed. The band in the box is the median and the under quartile is the 25 % value while the upper quartile is the 75% value. The whiskers represent 1.5 IQR and the dots are samples outside that range, outliers. A) All available data of N-fertiliser usage, n=60 B) All available data of nitrate-N concentrations, n= 33. C) Usage of N-fertiliser for SIPSIN-WAS farmers, n=23. D) Nitrate-N concentrations for the SIPSIN-WAS farmers, n=23. The dashed lines mark WHO guideline.

In Figure 12D there were no strong evidence that the concentration of nitrate in Robit Bata differed during 2017. However, in Table 2 the results from the Wilcoxon signed rank test for SIPSIN-WAS nitrate-N indicates that some months are significantly different from each other. The last three months differed from the two first. In addition, October, November and December also differed from May.

Table 2. The p-values of the Wilcoxon signed rank test performed on the SIPSIN-WAS nitrate-N data grouped by month for Robit Bata watershed. The numbers in red mark when the null hypothesis was rejected, p-value < 0.05. A rejected null hypothesis indicates that the compared groups are significantly different. Values where p-value could not be computed exactly due to ties or zeros are marked with "tz"

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan												
Feb	0.732											
Mar	0.200	0.012										
Apr	0.033	0.012	0.035									
May	0.286	0.823	0.006	0.001^{tz}								
Jun	0.687	0.482	0.501	0.200	0.286							
Jul	0.622	0.580	0.601	0.445	0.482	0.867						
Aug	0.023	0.021	0.315	0.601	0.023	0.086	0.687					
Sep	0.501	0.323	0.560	0.160	0.136^{tz}	0.988	0.893	0.111				
Oct	0.010	0.002	0.049	0.300	0.001	0.136^{tz}	0.560	0.823	0.086			
Nov	0.042	0.030	0.256	0.445	0.015	0.151	0.560	0.399^{tz}	0.218	0.731		
Dec	0.003	0.001	0.190	0.988^{tz}	0.003	0.160	0.445	0.780	0.125	0.808^{tz}	0.643	

In Dangishta the yearly N-fertiliser application among the farmers (n=37) varied between 18.0 - 217.3 kg N with a median of 87 kg N. The yearly median and maximum N-fertiliser application in Robit Bata (n=60) was greater, 109.4 and 276.3 kg N, compared to Dangishta but two farmers did not use fertilisers making the minimum zero. The monthly median application of N-fertilisers was similar in the watersheds. The median application was zero for all months except June and July for Dangishta (27 and 46 kg N), Figure 11A, and for Robit Bata the application was above zero in June, July and August (33.4, 46 and 2.7 kg N), Figure 12A.

In Figure 13, the concentration of nitrate-N, grouped by well ID, for all the wells in the two watersheds are presented (n=23 and n=33). In Dangishta watershed, the nitrate-N concentration varied among the wells with the highest median value (9.38 mg l^{-1}) found in W16. W16 was among the wells with largest IQR, indicating the concentration differed a lot over the year. In comparison to Dangishta, the concentrations of nitrate-N in the wells of Robit Bata was more homogeneous. The median value of the nitrate-N concentration was around 5 mg l^{-1} or lower for all wells and eleven of total 396 measurements exceeded the guidelines from WHO. In Appendix C, tables summarising the exceedance of WHO guidelines can be seen.

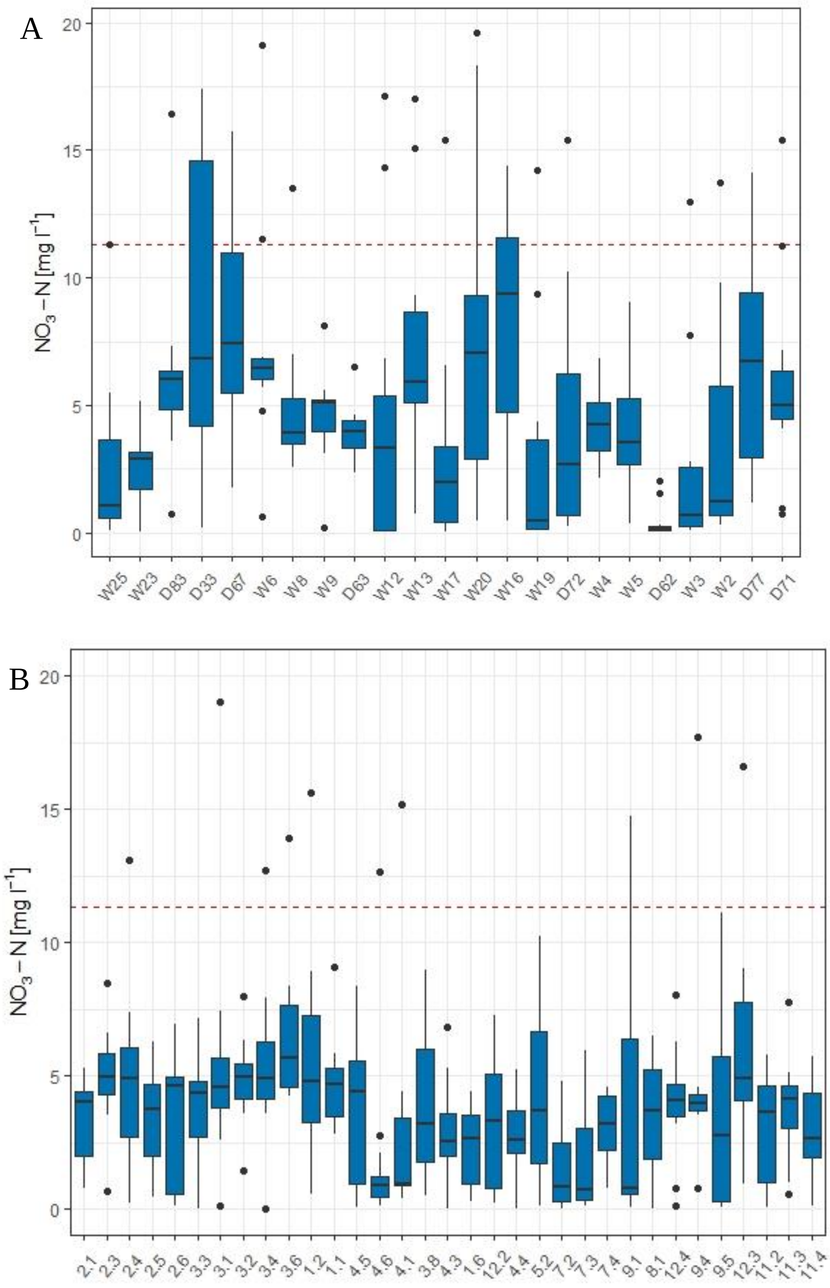


Figure 13. A) Box plot of the concentration of nitrate-N for the wells in Dangishta watershed, (n=23). B) Box plot of the concentration of nitrate-N for the wells in Robit Bata watershed, (n=33). The whiskers represent 1.5 IQR and the dots are samples outside that range, outliers. The dashed lines mark WHO guideline. The wells are geospatially ordered.

The concentration of nitrate-N for the SIPIN-WAS wells in the Dangishta watershed plotted along with information about N-fertiliser applied by the household show that a high application of nitrogen not necessarily results in a high concentration of nitrate-N in the wells, Figure 14. The plots show that even if the highest number of N-fertilisers were applied in June and July the response in nitrate concentration differed among the wells. The drainage analysis (Figure 7 and Figure 8) showed that no wells were connected and only the drainage area of wells D67 included other households in WAS. Anyhow, a strong relationship between the amount of nitrogen fertiliser and nitrate-N concentration cannot been seen from the plots in Figure 14.

One of the households with two wells, household ID120 with the wells W8 and D63, have quite similar levels of nitrate-N concentration during the year but with the high value in July standing out for W8. Well W9 is situated very close to W8 and D63 (Figure 4) and showed a similar pattern but have instead a very low value for July. The wells in the other household with two wells, ID107 and well W6 and D67, have more fluctuation in the data. W6 is located just next to the house whereas D67 is located on a field about 50 m away.

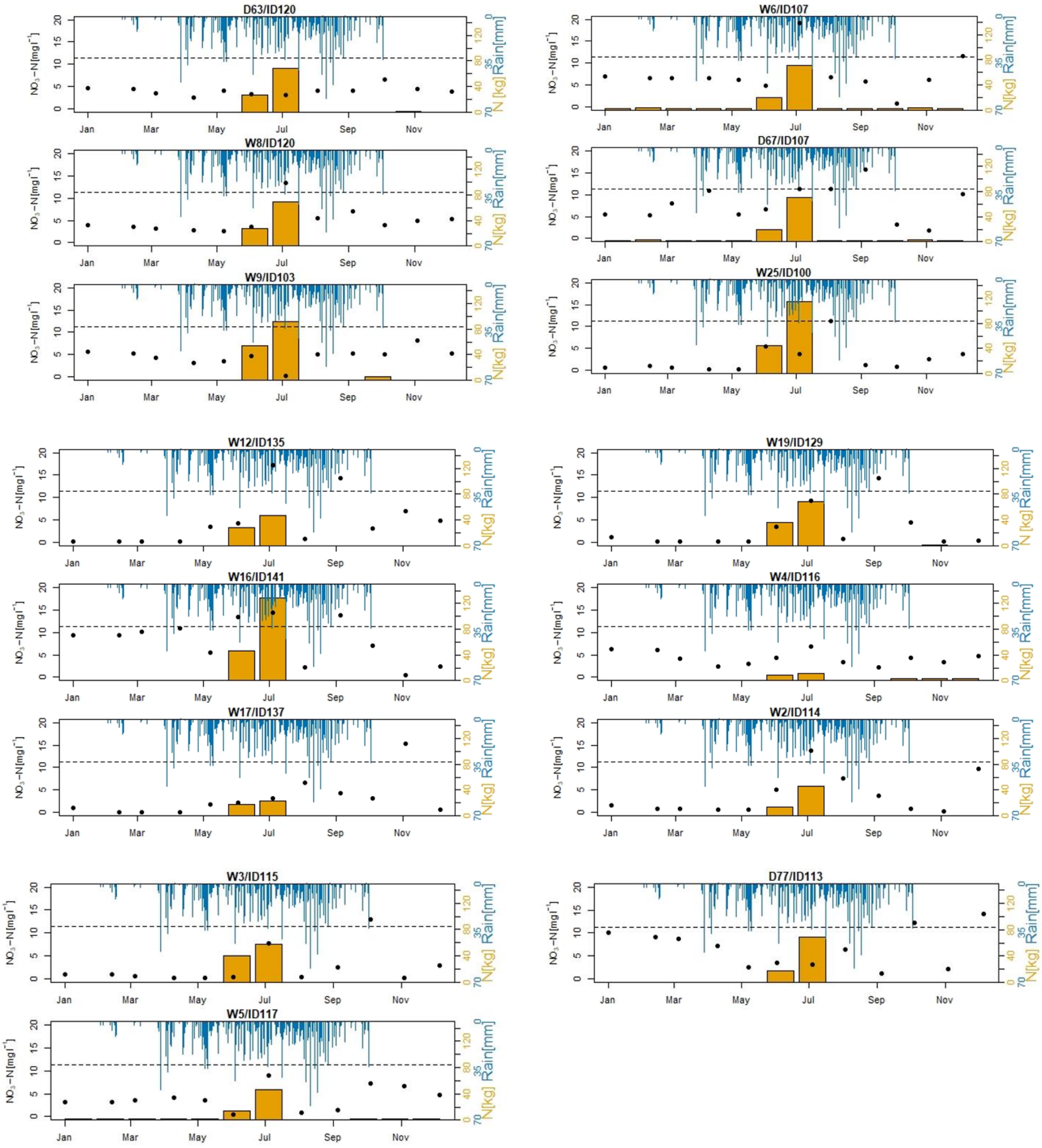


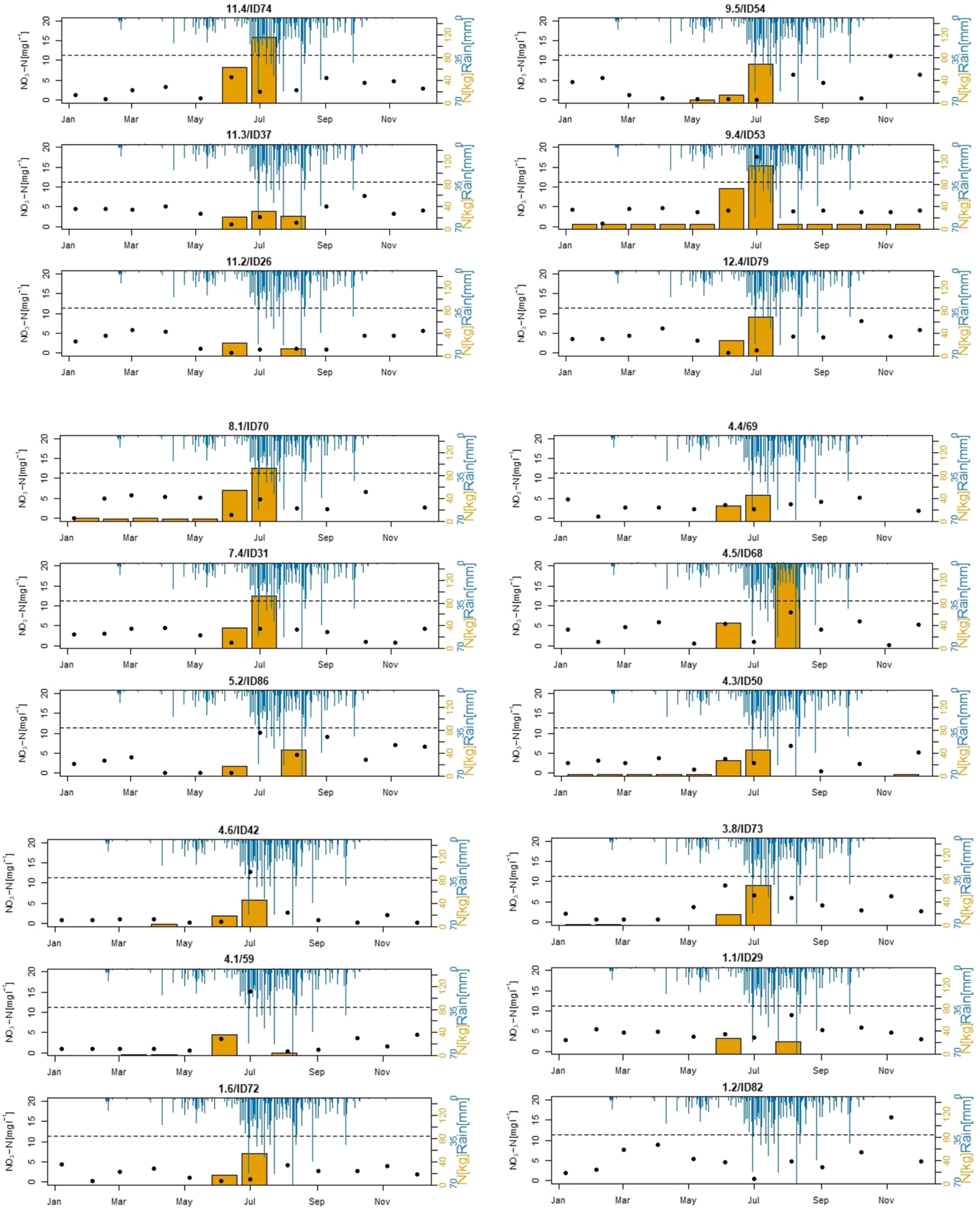
Figure 14. Rainfall, monthly applied nitrogen fertiliser and concentration of nitrate-N for SIPSIN-WAS farmers in the Dangishta watershed. In each subplot concentration of nitrate, visualised by black dots, is found on the left y-axis and N-fertiliser, visualised by orange bars, is found on the right y-axis. The blue bars found on the upper x-axis represent daily rainfall events.

The results of the Kendall´s tau correlation between nitrate-N concentration and N-fertiliser or precipitation, respectively, can be seen in Table 3. In line with observations for Figure 14 above, the significant correlations between the parameters were low. Positive correlations between N-fertiliser and nitrate concentration were expected but two wells with negative correlations occurred. Negative correlation occurred for precipitation as well. For well D67 with a drainage area involving other households, a supplementary correlation test was done adding corresponding N-fertilisers, but no significant correlations were found except for two-month delay (tau=0.68, p-value=0.004).

Table 3. The correlation coefficients of the Kendall´s tau test for the SIPSIN-WAS in Dangishta watershed. Only correlation coefficients with significant correlation are presented (p-value < 0.05). The first column represents a direct response between N-fertiliser applied and concentration of nitrate-N whereas the rest represents a delay in response of one, two or three months. The same applies for precipitation

	N-FERTILISER				PRECIPITATION			
Well	Direct	One-month delay	Two-month delay	Three-month delay	Direct	One-month delay	Two-month delay	Three-month delay
D63								
W8		0.54						0.53
W9								
W6		0.56		-0.58				
D67		0.48	0.56		0.48			
W25								
W12							0.50	0.50
W17						0.54	0.69	0.56
W19								
W16	0.51							
W4								
W3								
W5			-0.55					
W2								
D77						-0.45		

As stated earlier, the nitrate-N concentrations were generally lower in the Robit Bata watershed compared to Dangishta. However, some fluctuations over the year can be seen for individual wells, Figure 15. The single highest nitrate-N concentration in Robit Bata was found in well 9.4 and just as in Dangishta the value was found in July. For four individual wells (1.2, 2.4, 3.4 and 3.6) the highest values were found in November and these values also exceeded the WHO guidelines. These wells were found in the same part of the watershed, but nearby wells did not have the same response. The remaining wells that also exceeded the WHO guidelines, well 4.1 and well 4.6, were spatially close (Figure 5) and had just like 9.4 their highest value in July. When comparing the sum of total N-fertiliser applied in 2017 and the maximum nitrate-N values, four of the highest concentrations were found among the eight farmers with highest N-fertiliser load. On the other hand, the remaining three wells that exceeded the WHO guidelines were found among the seven households with least nitrogen load. Regarding the wells with drainage area affected by other wells or households, the nitrate-N concentration in well 11.4 located near the outlet of the watershed fluctuated a bit over the year but never exceeded the WHO guidelines. The nitrate-N variation for well 9.1 exceeded the WHO recommendations in May and June but were low the rest of the year with exception for October where the concentration reached 10 mg l^{-1}.



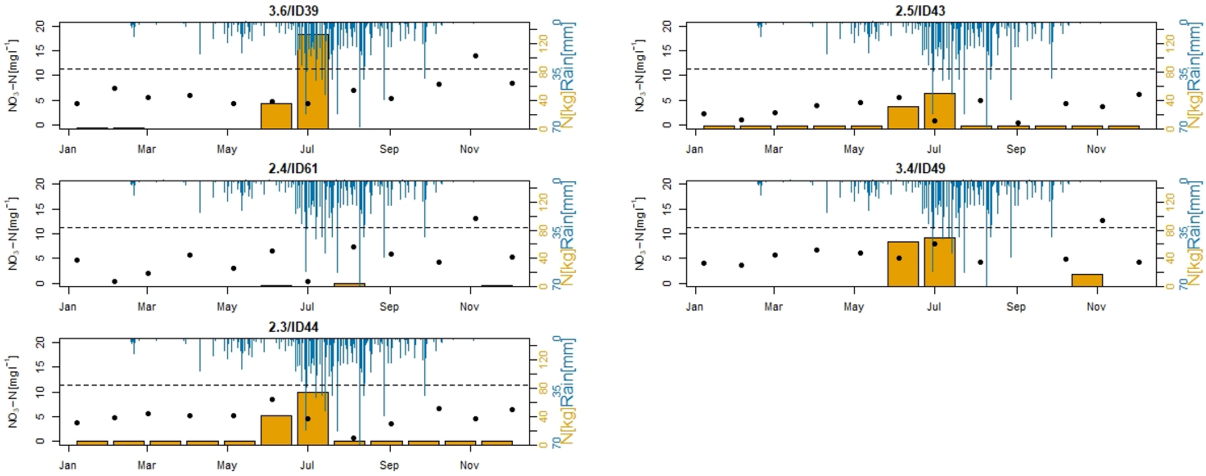


Figure 15. Rainfall, N-fertiliser and concentration of nitrate-N for SIPSIN-WAS farmers in the Robit Bata watershed 2017. In each subplot concentration of nitrate, visualised by black dots, is found on the left y-axis and N-fertiliser, visualised by orange bars, is found on the right y-axis. The blue bars found on the upper x-axis represent daily rainfall events.

Table 4 shows the Kendall´s tau results for Robit Bata watershed and like Dangishta, both positive and negative correlations occur between nitrate-N concentration and N-fertiliser as well as precipitation. For well 1.2 no correlation between N-fertiliser and nitrate could be computed since there was no usage of fertilisers on the corresponding farm. Supplementary correlation tests were done for well 11.4 adding corresponding N-fertilisers from the drainage area, but no significant correlations were found. In addition, correlation tests were done for well 9.1 but no significant correlations occurred.

Table 4. The correlation coefficients of the Kendall’s tau test for the SIPSIN-WAS in Robit Bata watershed. Only correlation coefficients with significant correlation are presented (p-value < 0.05). The first column represents a direct response between N-fertiliser and concentration of nitrate-N whereas the rest represents a delay in response of one, two or three months. The same applies for precipitation

	N-FERTILISER				PRECIPITATION			
Well	Direct	One month delay	Two month delay	Three month delay	Direct	One month delay	Two month delay	Three month delay
1.1				-0.51				
1.2	-	-	-	-				
1.6								
2.3								
2.4								
2.5								
3.4								
3.6								0.48
3.8				0.48	0.44			
4.1								
4.3								
4.4								
4.5								
4.6								
5.2		0.51						
7.4								
8.1							-0.54	
9.4								
9.5	-0.68						0.48	0.64
11.2								0.48
11.3	-0.54							
11.4					0.44	0.51		
12.4	-0.51							

5.2.1 Livestock

The holding of livestock among the farmers in Dangishta watershed (n=37) varied between 0.7 and 11 TLU with a median of 4.7 TLU. The monthly potential nitrogen extraction of manure from the same households varied between 1.3 and 19.3 kg N with a median of 8.3 kg N, Table 5. The highest monthly nitrogen potential from manure was found in the drainage area of D67 with a corresponding maximum nitrate-N of 15.70 mg l^{-1} which is above the WHO guidelines. The second highest monthly potential was found in well W4 but the nitrate-N concentration of 6.84 mg l^{-1} was with margin below the WHO guideline. Furthermore, the lowest monthly manure potential was found in well W17 which had a maximum nitrate-N value of 15.40 mg l^{-1}. The Kendall´s tau correlation coefficients between the potential monthly nitrogen extraction from manure and minimum, median and maximum of nitrate-N concentration were low and one even negative (0.34, 0.29 and -0.11) and had p-values > 0.05 (0.07, 0.14 and 0.55) indicating that there were no significant relations between TLU and any of the parameters tested here.

Table 5 also shows that both wells with larger and smaller drainage areas had maximum values that exceeded the WHO-guidelines. The drainage analysis (Figure 8) showed that well D63 and well W9 had the same drainage area, however their maximum value of nitrate-N differed. Well D63 had a maximum value of 17.40 whereas W9 had a maximum value of 8.10. No significant correlations between drainage area and minimum, median and maximum of nitrate-N concentration were found (p-values 0.29, 0.57 and 0.79).

Table 5. Drainage area, monthly potential nitrogen extraction from manure and concentrations of nitrate-N in Dangishta watershed. The symbol "–" indicates that the well was not included in WAS and no value could be calculated

		MANURE [kg]	NITRATE- N [mg l^{-1}]		
Well	Drainage area [m2]	Monthly nitrogen potential	Min	Median	Max
D83	30,190	-	0.77	6.03	16.40
D67	29,246	22.16	1.78	7.42	15.70
W12	21,699	8.25	0.06	3.32	17.12
W13	14,151	-	0.77	5.92	17.02
W8	13,208	4.23	2.58	3.91	13.50
W3	10,378	6.84	0.09	0.71	13.00
W19	9,434	10.73	0.08	0.50	14.22
W5	9,434	12.42	0.37	3.55	9.06
W2	8,491	8.04	0.29	1.24	13.72
D71	7,547	-	0.75	4.99	15.40
W4	7,547	19.33	2.16	4.25	6.84
D72	4,717	-	0.25	2.68	15.40
D77	2,830	14.80	1.18	6.75	14.10
D33	1,887	-	0.19	6.83	17.40
D62	1,887	-	0.03	0.17	2.06
D63	943	4.23	2.38	6.83	17.40
W16	943	17.43	0.46	9.38	14.40
W17	943	1.34	0.07	1.99	15.40
W20	943	-	0.46	7.04	19.60
W23	943	-	0.05	2.88	5.18
W25	943	6.73	0.12	1.05	11.30
W6	943	6.87	0.66	6.48	19.10
W9	943	10.11	0.22	5.13	8.10

In Robit Bata watershed the minimum and median TLU values were lower than in Dangishta (0 and 3.5) but the maximum value of 17.2 TLU was higher (n=60). The statistics regarding the monthly potential nitrogen extraction from manure follow the same pattern with the minimum and median being lower (0 and 6.7) while the maximum value of 32.5 kg N being higher in Robit Bata compared to Dangishta. The monthly nitrogen potential was highest in the drainage area of well 11.4 but was not reflected in the nitrate-N concentration in the corresponding well, Table 6. Notable was that all nitrogen potential came from other households in the watershed since the household of 11.4 had no livestock. Like Dangishta, the Kendall´s tau correlation coefficients between potential monthly nitrogen extraction from manure and minimum, median and maximum of nitrate-N concentration were low and there were no significant correlations, p-values 0.64, 1 and 0.36. Furthermore, there were no significant correlation between drainage area and nitrate-N statistics, p-values 0.79, 0.11 and 0.80.

Table 6. Drainage area, monthly potential nitrogen extraction from manure and concentrations of nitrate-N in Robit Bata watershed. The symbol "–" indicates that the well was not included in WAS and no value could be calculated

		MANURE [kg]	NITRATE- N [mg l^{-1}]		
Well	Drainage area [m^2]	Monthly nitrogen potential	Min	Median	Max
11.4	13,720,009	438.13	0.10	2.62	5.70
9.1	5,921,737	39.72	0.07	0.75	14.70
4.6	65,125	6.70	0.14	0.88	12.66
8.1	38,145	15.32	0.04	4.68	6.48
4.4	35,354	1.55	0.45	2.62	5.22
3.4	27,911	6.76	3.60	4.96	12.68
2.5	20,468	5.36	0.43	3.76	6.26
1.1	18,607	4.02	2.83	4.67	9.04
3.8	17,677	3.53	0.51	3.21	8.98
4.3	16,746	5.36	0.52	2.63	6.80
12.2	16,746	-	0.92	3.28	7.28
5.2	12,095	4.05	0.10	3.70	10.20
1.2	11,173	5.36	0.57	4.79	15.60
7.4	11,164	5.36	0.75	3.18	4.54
9.5	11,164	6.70	0.06	2.73	11.10
3.6	9,304	9.38	4.24	5.68	13.90
12.4	8.373	0.00	0.11	4.05	8.04
9.4	6,513	10.78	0.79	3.98	17.70
7.3	5,582	-	0.09	0.72	5.92
3.2	4,652	-	1.44	4.94	7.98
11.3	4,652	32.48	0.56	4.13	7.74
2.1	3.721	-	0.75	4.00	5.26
7.2	3,721	-	0.00	0.81	4.80
11.2	2,791	5.39	0.08	3.65	5.77
12.3	1,861	-	0.22	4.87	16.60
2.3	1,861	9.38	0.64	4.96	8.44
1.6	930	4.02	0.30	2.62	4.38
2.4	930	0.70	0.24	4.91	13.10
2.6	930	-	0.12	4.60	6.94
3.1	930	-	0.13	4.56	19.00
3.3	930	-	0.63	4.60	7.16
4.1	930	8.04	0.37	0.95	15.16
4.5	930	12.09	0.06	4.40	8.36

5.2.2 Irrigation

The irrigation practises in Dangishta varied among the farmers. 57% of the farmers (n=37) reported that they irrigated during dry season and 41% both irrigated and used fertilisers. Among the SIPSIN-WAS farmers (n=13) 38% both irrigated and used fertilizers in the dry season. The irrigated crops among farmers where shrubs (coffee, gesho and khat), fruit trees (orange, lemon, banana) and vegetables (tomato, onion, garlic, green pepper). Due to missing information about irrigation habits, weekly amount could only be calculated for one farmer (7.2 mm). This fact limited the analysis of possible links to water quality. However, the N-fertiliser application was low during the irrigation season, Figure 11, and given the type of crops and water abstraction techniques behaviour causing leakage seems unlikely. Still, the WHO guidelines were exceeded for several wells, Table 7.

In Robit Bata watershed 92% (n=60) of the farmers irrigated during the dry season and 75% used fertilisers. The irrigated crops were similar to Dangishta (i.e coffee, gesho, khat, tomato, onion, garlic and green pepper). The irrigation started earlier for some household in Robit Bata compared to Dangishta and the percentage of monthly irrigation was also bigger, Table 7. Among the four SIPSIN-WAS wells (n=23) that exceeded the WHO guidelines in November only one applied fertiliser in November. In addition, none of these household had applied anything since August or June. This could imply that the high value is not caused by the direct combination of N-fertiliser and water. The amount of irrigation could be calculated for 14 of the SIPSIN-WAS farmers and varied between 0.3-22.4 mm week^{-1}.

Table 7. Percentage of households (HH) that irrigate during a specific month and number of times the WHO guideline value of 11.3 mg l^{-1} nitrate- N were exceeded

	DANGISHTA				ROBIT BATA			
Month	% HH irrigate in watershed (n=37)	Times exceeded WHO limit	% SIPSIN-WAS irrigate (n=13)	Times exceeded WHO limit	% HH irrigate in watershed (n=60)	Times exceeded WHO limit	% SIPSIN -WAS irrigate (n=23)	Times exceeded WHO limit
Oct	-	-	-	-	16.7	0	21.7	0
Nov	18.9	3	30.8	1	68.3	5	82.6	4
Dec	48.6	5	61.5	2	83.3	0	100.0	0
Jan	51.4	0	61.5	0	83.3	0	100.0	0
Feb	56.8	0	76.9	0	80.0	0	100.0	0
Mar	56.8	0	76.9	0	75.0	0	95.7	0
Apr	56.8	0	76.9	0	66.7	0	82.6	0
May	48.6	0	61.5	0	65.0	0	82.6	0

5.3 NITRITE AND AMMONIA

The nitrite concentration in the two watersheds never exceeded the WHO guideline of 0.91 mg l^{-1}. The IQR for all months in both watersheds are quite small. However, an outlier in May for both watersheds could been seen, Figure 16. The concentrations are generally lower in Dangishta.

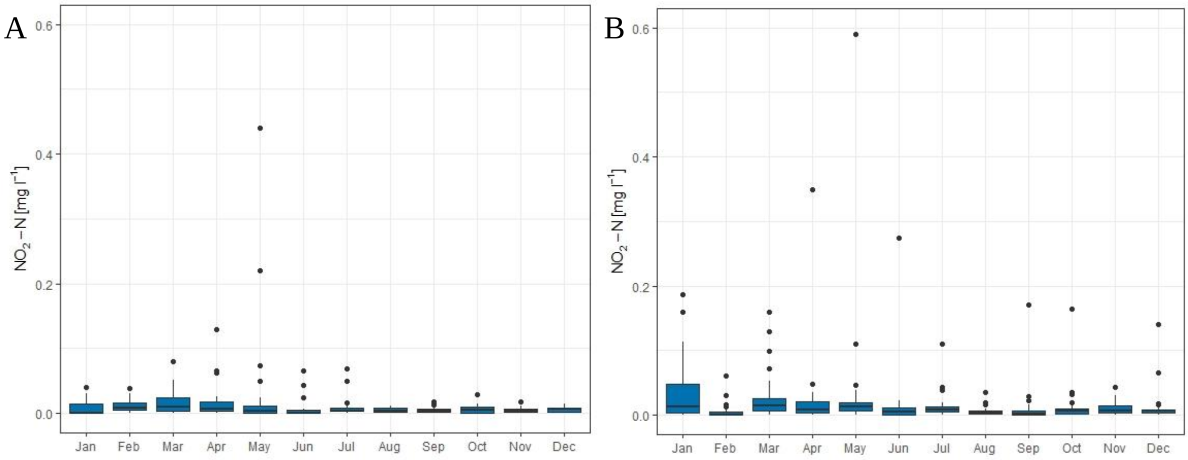


Figure 16. Nitrite-N concentrations in Dangishta (A) and Robit Bata (B) during 2017. The wishers represent 1.5 IQR and the dots are samples outside that range, outliers.

Figure 17 shows that the concentration of ammonia-N is low in both watersheds as well as the the IQR. Note that many of the samplings (93 for Robit Bata and 86 for Dangishta) were assigned with half of non-zero measuring range making the result not completely accurate (see section *4.1.2 SIPSIN-data*).

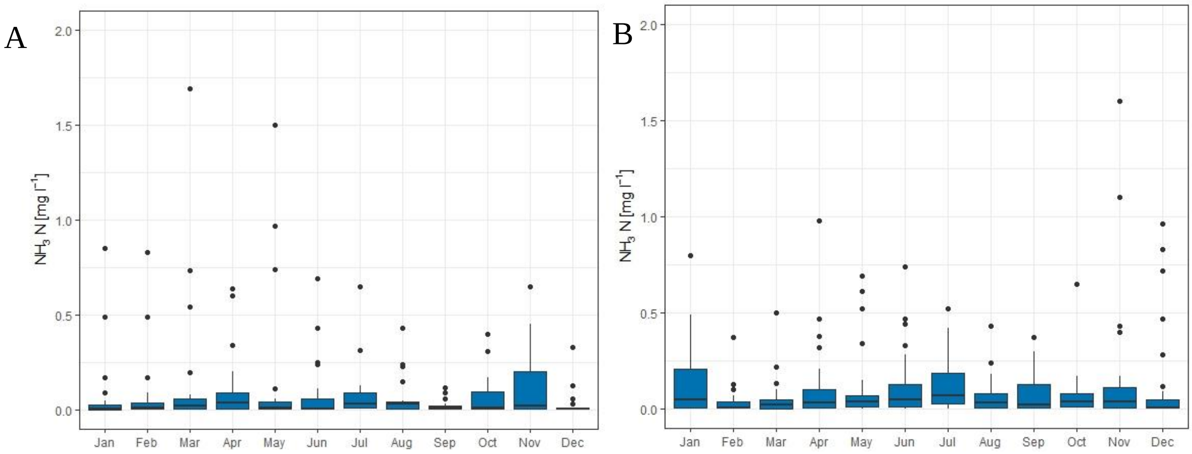


Figure 17. Ammonia-N concentrations in Dangishta (A) and Robit Bata (B) during 2017. The wishers represent 1.5 IQR and the dots are samples outside that range, outliers.

6 DISCUSSION

The initial expectations for this report was to explain spatial and temporal well water quality aspects linked to nitrogen. From what could be seen from this study, the concentration of nitrate in the wells were generally higher in Dangishta watershed compared to Robit Bata, and the WHO guideline was exceeded more frequently in Dangishta. The result was a bit nonintuitive given that irrigation practices were more expanded, and the yearly application of fertiliser was slightly higher in Robit Bata watershed compared to Dangishta. However, the median TLU value was a bit higher in Dangishta.

In the analysis done in this paper, no general explanation of nitrate response in the wells could be found. Wells with large drainage area, particularly well 9.1 and 11.4 in Robit Bata, did not reflect the potentially large nitrogen contribution. In fact, 11.4 never exceeded the WHO guidelines and 9.1 did it only occasionally. In the flatter Dangishta watershed the range in drainage area size was smaller than in Robit Bata but no correlation between drainage area and nitrate concentration in wells could be seen in any of the watersheds. Furthermore, no correlation between potential nitrogen from TLU and concentrations in wells could been seen. Tilahun et al. (in prep) stated that the dominated runoff principle in hillside areas in Robit Bata was subsurface lateral flow and the surface runoff was small. If this being the case, soil properties and chemical reactions within the soil become important for the contamination levels since transformation of compounds and uptake by crops will influence the amount of nitrogen passing the root zone. Engda el al. (2011) described that surface runoff could be generated from saturated areas, often in flatter part of the landscape. Hypothetically this could be related to the differences in concentrations between Robit Bata and Dangishta on watershed scale, assuming potentially more surface runoff in Dangishta resulting in a greater portion of the applied nitrogen ending up in the wells. In Dangishta the WHO guidelines were exceeded most frequently in July and September when the groundwater table is close to the surface area. However, the drainage analysis from Dangishta watershed showed that the contributing areas to the wells were small in several cases, making the explanation above less likely.

The drainage analysis assumed that the flow followed the topography of the watersheds and perhaps the lack of correlation between the parameters is based on this. When comparing drainage lines from the analysis with the outline of the streams, based on images from Google Earth, some differences can be seen, Appendix D. Of course, differences are expected but especially for Robit Bata, when the differences are more distinctive, it can indicate that the simplified assumption used is not totally accurate.

The rainfall data was collected from stations in the cities of Dangila and Bahir Dar respectively. The distance from the station to the watersheds as well as the topography variation within the watersheds might have influenced the distribution of rain. It is hard to tell if the topography influences the rain pattern and if it will have an influence on the results, but it is a possibility. Furthermore, the amount of rain fallen in 2017 differed with the amount in Dangishta watershed (2025 mm) being greater than in Robit Bata watershed (1560 mm). Dangishta watershed exceeded the WHO guidelines more often than Robit Bata concerning nitrate-N levels in the wells, but as stated earlier, no general patterns in correlations between precipitation and contamination levels in the wells were found in any of the two watersheds. However, correlation between concentration of nitrate-N and precipitation as well as concentration of nitrate-N and applied amount of N-fertiliser occurred for some specific wells. Among the wells where correlation occurred, positive correlation occurred most frequently. For one well in each watershed, negative correlation between concentration of nitrate-N and precipitation occurred, which could be a consequence of the dilution of nitrate caused by rain. Negative correlation between concentration of nitrate-N and applied amount N-fertiliser, which occurred in two cases for Dangishta and four cases for Robit Bata, could be explained by the growing process of crops; N-fertilisation stimulates the growing process which results in a higher nitrogen uptake by the roots of the crop.

Saturation excess runoff directly into the wells from the ground surface might theoretical be an issue during heavy rainfall. However, most of the wells observed in field where either covered by some sort of cap for protection or having the well-hole over the ground surface (see Appendix E for pictures).

One of the weaknesses in the procedure and a big assumption was that the nitrogen applied on the fields or generated by livestock for a specific farmer will end up in the farmers well. Both watersheds, especially Robit Bata, is dominated by agriculture land use making the neighbouring farmers habits of importance and the livestock is usually free grazing. An attempt to pass this problem was to consider the flow patterns and contributing area to the wells to evaluating possible connections, but no obvious relation could be seen. However, since the contributing drainage area for several wells were small, even if located downslope, the possibility of livestock grazing at the specific area was low. The usage of organic fertilisers on the fields were most common in the irrigation season, but the low nitrogen content (1.83%) would make an extensive leakage causing the peaks seen in November for some wells in Robit Bata unlikely. Furthermore, looking at the land use map in combination with the drainage area (Appendix F) no big areas of irrigated crops could be found. Human behaviour or habits around the wells might also have potential to influence the contamination levels found in the wells. This study did not involve factor such as the position of toilets, which is a possible factor contribute to nitrogen load.

To summarise, the simplified hydrological approach used in this paper cannot explain the spatial and temporal variation in well water nitrogen concentrations in the watersheds. For example, in Dangishta two wells had the exact same drainage area but a big difference in maximum concentrations. The method also relied on data from interviews requiring the farmers doing estimations and remember information from several months back, which of course brought some uncertainties to the analysis. Contradictory information in overlapping questions also occurred in the survey material indicating that material was not the most reliable. Furthermore, the information in the survey was sorted by month and accordingly not capturing if the fertiliser were applied in the beginning, end or evenly distributed during the month. The field visits performed in autumn 2018 for complementary survey information were done with an enumerator since the author of the report did not speak the local language. This may have led to misunderstandings and a more extensive correction of the data resulting in more reliable results, could perhaps have been done by native authors.

The study was based on an extensive data material where the survey and the water quality data by themselves provide important information about the agricultural habits and water quality in the watersheds. However, combining the survey and water quality data failed to explain the nitrogen levels in the wells, which was the main intention with the study. One possible explanation to this is that there is no single explanatory factor, but rather many factors combined that influence the nitrogen levels in the groundwater. Using multiple regression, or similar methods, might possibly be able to explain such integrated impacts, but this was not conducted in this study. However, the study indicated that the explanation might be site specific, and to improve the results, a greater overlapping between the survey and the water quality data would be desirable. Evaluations including more precise details on crop management and subsurface flow patterns as well as on other factors influencing contamination levels in wells, such as distance to household and cattle, are needed in further investigations as agriculture continues to intensify.

The main outcome from this study was that the WHO guidelines were occasionally exceeded in some of the wells, even if the intensification of the watersheds was relatively low. An increasing uncontrolled intensification might result in higher contamination levels in the wells which could be a serious health issue if the groundwater will be used as drinking water in the future. This implies that actions need to be taken to secure water safety for the inhabitants by, for example, opting for sustainable agricultural management.

7 CONCLUSIONS

There were temporal changes in water quality for both watersheds. In Dangishta the median nitrate-N concentration was highest in July and the month was significantly different from all other except August, September and October. Furthermore, December was significantly different from February, March, May, June and July. For Robit Bata April, August, October, November and December were significantly different from January, February and May. The median concentrations of nitrate-N were generally lower in Robit Bata than Dangishta but the nitrite and ammonia were quite similar in both watersheds. The WHO guideline was most frequently exceeded in July and November (5 times) for Robit Bata and July and September (7 times) for Dangishta.

No relationships between N-fertiliser, precipitation and concentration of nitrate could be seen for any of the two watersheds. The information about irrigation was inadequate so no conclusion based on statistics could be made. However, the results indicated that there was no relationship between irrigation and contamination levels in the wells. No relationship between livestock and contamination level could be statistically determined. The results implied that the nitrate response in the wells were site specific since differences between geospatially close wells differed.

The method used in this paper could not explain the contamination levels in the wells, but the results showed that the water quality in both watersheds was occasionally poor.

REFERENCES

Atinkut, H (2005). Adoption of conservation agricultural practices: The case of Dangila District, Amhara Region, Ethiopia. *Global Journal of Agricultural Economics, Extension and Rural Development*, Vol. 3 (9), pp. 295-307.

Anthonisen, A., Loehr, R., and Prakasam T. and Srinath E. (1976). Inhibition of Nitrification by Ammonia and Nitrous Acid. *Water Pollution Control Federation,* 48(5), pp. 835- 852.

Burkart, M. and Stoner, J. (2001). 'Nitrogen in Groundwater Associated with Agricultural Systems', in Follet, R. and Hatfield, J (ed.) *Nitrogen in the environment.* Amsterdam: Elsevier, pp. 123-138.

Chianu, J., Chianu, J. and Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agronomy for Sustainable Development,* 32(2), pp.545-566.

Conley, D., Paerl, H., Howarth, R., Boesch, D., Seitzinger, S., Havens, K., Lancelot, C. and Likens, G. (2009). Controlling Eutrophication: Nitrogen and Phosphorous. *Science,* 323, pp 1014-1015.

Domenico, P. and Schwartz, F. (1998). *Physical and chemical hydrogeology*. 2nd ed. New York: John Wiley & Sons, Inc, pp.34, 76-78, 83-85.

ELE International (n.d). Operating Instructions: Paqualab Photometer 430-550.

Engda, T., Bayabil, H., Legesse, S., Tilahun, S., Collick, A., Easton, Z., Rimmer, A., Awulachew, S. and Steenhuis., S. (2011) Watershed Hydrology of the (Semi) Humid Ethiopian Highlands. In: Melesse A.M. (eds) Nile River Basin. Springer, Dordrecht

Eriksson, J., Dahlin, S., Nilsson, I. and Simonsson, M. (2011). *Marklära*. 1st ed. Lund: Studentlitteratur, pp.269-278.

European Space Agency (2004). Lake Tana, Source of the Blue Nile. Available: (http://www.esa.int/Our_Activities/Observing_the_Earth/Lake_Tana_source_of_the_Blue_Nile [2018-05-02].

FAO. (2011). *Climate Change and Food Systems Resilience in Sub-Saharan Africa*. Rome: Food and Agriculture Organization of the United Nations. Available: http://www.fao.org/3/i2230e/i2230e.pdf [2018-05-18]

Finch, S. and Samuel, A. (2002). Lockhart & Wiseman's Crop Husbandry - Including Grassland (8th Edition). Woodhead Publishing.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P. A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J. H., Townsend, A. R. and Vörösmarty, C.J. (2004). Nitrogen Cycles: Past, Present, and Future. *Biogeochemistry,* 70(2), pp. 153-226.

Gbenou, B., Adjolohoun, S., Ahoton, L., Houndjo, D., Saïdou, A., Houinato, M. and Sinsin, B. (2017). Animal dung availability and their fertilizer values in a context of low soil fertility conditions for forage seed and crops production in Benin (West Africa). *American Journal of Agricultural Research*, pp.1-14.

Geyer, D., Keller, C., Smith, J. and Johnstone, D. (1992). Subsurface fate of nitrate as a function of depth and landscape position in Missouri Flat Creek watershed, U.S.A. *Journal of Contaminant Hydrology*, 11(1-2), pp.127-147.

Glibert, P., Harrison, J., Heil, C. and Seitzinger, S. (2006). Escalating Worldwide use of Urea – A Global Change Contributing to Coastal Eutrophication. *Biogeochemistry*, 77(3), pp.441–463.

Grip, H. and Rodhe, A. (2009). *Vattnets väg från regn till bäck*. Uppsala: Hallgren & Fallgren Studieförlag AB.

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D. and Lesschen, J. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystems & Environment*, 108(1), pp.1-16.

Hellsten, S., Dalgaard, T., Rankinen, K., Tørseth, K., Kulmala, A., Turtola, E., Moldan, F., Pria, K., Piil, K., Bakken, K., Bechmann M. and Olofsson, S. (2017). *Nordic nitrogen and agriculture Policy, measures and recommendations to reduce environmental impact*. Denmark: Nordic Council of Ministers. Available at: https://norden.diva-portal.org/smash/get/diva2:1135119/FULLTEXT01.pdf [Accessed 20 Mar. 2019].

Hou, Y., Bai, Z., Lesschen, J., Staritsky, I., Sikirica, N., Ma, L., Velthof, G. and Oenema, O. (2016). Feed use and nitrogen excretion of livestock in EU-27. *Agriculture, Ecosystems & Environment*, 218, pp.232-244.

IPCC (2014). *Climate Change 2014: Synthesis Report.* Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

International Plant Nutrition Institute. (n.d.). Nutrient Source Specifics – Diammonium Phosphate [online] Available at: https://www.ipni.net/publication/nss.nsf/0/66D92CC07C016FA7852579AF00766CBD/$FILE/NSS-17%20Diammonium%20Phosphate.pdf [Accessed 5 Dec. 2018].

Lupwayi, N., Girma, M. and Haque, I. (2000). Plant nutrient contents of cattle manures from small-scale farms and experimental stations in the Ethiopian highlands. *Agriculture, Ecosystems & Environment*, 78(1), pp.57-63.

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M. and Vanlauwe, B. (2017). Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review. *Soil Research*, 55(6), p.425.

Moges, A., Schmitter, P., Tilahun, S. and Steenhuis, T. (2018). Watershed modeling for reducing future non-point source sediment and phosphorus load in the Lake Tana Basin, Ethiopia. J Soils Sediments. DOI 10.1007/s11368-017-1824-z

Mulugeta, M. A. (2013). Modeling and Analysis of Lake Tana Sub Basin Water Resources Systems, Ethiopia. Diss. Rostock, Germany: Rostock University.

National Meteorology Agency (2018). Dangila station – daily rainfall in mm. Available: http://www.ethiomet.gov.et/data_access/request_form

National Meteorology Agency (n.d.). Climate of City: Bahir Dar. [online] Available at: http://www.ethiomet.gov.et/climates/climate_of_city/2648/Bahir%20Dar [Accessed 20 Mar. 2019].

Rimhanen, K. and Kahiluoto, H. (2014). Management of harvested C in smallholder mixed farming in Ethiopia. Agricultural Systems, 130, pp.13-22.

Rittenburg, R., Squires, A., Boll, J., Brooks, E., Easton, Z. and Steenhuis, T. (2015). Agricultural BMP Effectiveness and Dominant Hydrological Flow Paths: Concepts and a Review. *JAWRA Journal of the American Water Resources Association*, 51(2), pp.305-329.

Robinson, T.P., Thornton P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda, G. & See, L (2011), Global livestock production systems. Rome, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI), 152 pp

Schmitter, P. (2018). Dr and Agriculture Water Management Specialist. Unpublished letter.

Sheahan, M. and Barrett, C. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, 67, pp.12-25.

Stadler, S., Osenbrück, K., Knöller, K., Suckow, A., Sültenfusß, J., Oster, H., Himmelbasch, T. and Hötzl, H. (2008). *Understanding the origin and fate of nitrate in groundwater of semi-arid environments*. Journal of Arid Environments, doi:10.1016/j.jaridenv.2008.06.003

Steinfeld, H. and Wassenaar, T. (2007). The Role of Livestock Production in Carbon and Nitrogen Cycles. *Annual Review of Environment and Resources*, 32(1), pp.271-294.

The Editors of Encylopædia Britannica (2017). Runoff. In: *Encyclopædia Britannica*. Encyclopædia Britannica, inc. Available: https://www.britannica.com/science/runoff [2018-05-07]

Tilahun, S., Ayana, E., Guzman, C., Dagnew, D., Zegeye, A., Tebebu, T., Yitaferu, B. and Steenhuis, T. (2016). Revisiting storm runoff processes in the upper Blue Nile basin: The Debre Mawi watershed. *CATENA*, 143, pp.47-56.

Tilahun, S., Yilak, D., Schmitter, P., Langan, S., Barron, J., Parlange, J-Y and Steenhuis, T. (in prep.) Establishing irrigation potential of a hillside aquifer in the African highlands. Unpublished manuscript.

UN (2017). *World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100.* Available: https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html [2018-05-07]

UN General Assembly (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*, 21 October 2015, A/RES/70/1. Available: http://www.refworld.org/docid/57b6e3e44.html [2018-05-07]

Walker, D. (2015). *Provisional Geology and Hydrogeology Report for Dangila Woreda and Robit Bata Catchment*: Unpublished manuscript. Newcastle University

Walker, D., Forsythe, N., Parkin, G. and Gowing, J. (2016). Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *Journal of Hydrology*, 538, pp.713-725.

World Bank Data (2019). *Employment in agriculture (% of total employment) (modeled ILO estimate).* Available: https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?end=2018&locations=ET&start=1991&view=chart [2019-06-10]

World Health Organization (2017). Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Geneva, Licence: CC BY-NC-SA 3.0 IGO

Yehualie, D. (2019). *Evaluation of Shallow Ground Water Recharge and Irrigation Practices at Robet Watershed. Bahir Dar University*. Faculty of civil and water resource engineering (Master Thesis)

APPENDIX

A. WATER LEVEL IN WELLS

In Dangishta watershed, the deepest distances, from ground surface to groundwater level, among the wells (n=15) varied between 3.5 – 13.6 m and the shallowest distances varied between 0.45 – 9.12 m (Table A1). The deepest distances from ground surface to water level among the wells in Robit Bata watershed (n=23) varied between 5.10-17.00 m and the shallowest distances varied between 0.20-6.00 m (Table A2).

Table A1. Distance from ground surface to groundwater level in wells in Dangishta watershed

DANGISHTA WATERSHED			
ID	Max [m]	Min [m]	Difference [m]
W25	3.5	0.45	3.05
W9	8.85	6.15	2.7
D67	10.5	3.2	7.3
W6	10.5	2.32	8.18
D77	4.68	3.05	1.63
W2	10.25	2.08	8.17
W3	12.2	6.09	6.11
W4	10	6.36	3.64
W5	12.05	9.12	2.93
D63	10.5	5.3	5.2
W8	10.5	7.25	3.25
W19	12.3	3.15	9.15
W12	13.6	3.15	10.45
W17	8.4	1.25	7.15
W16	13.2	2.75	10.45

Table A2. Distance from ground surface to groundwater level in wells in Robit Bata watershed

ROBIT BATA WATERSHED			
ID	Max [m]	Min [m]	Difference [m]
1.1	14.5	6	8.5
1.2	8.3	3.3	5
1.6	9.35	0.7	8.65
2.3	12.1	0.4	11.7
2.4	16.2	4.2	12
2.5	13.5	3.2	10.3
3.4	17	3	14
3.6	12.7	3.7	9
3.8	7.2	4	3.2
4.1	11	2.6	8.4
4.3	13.8	3.6	10.2
4.4	14.2	1.9	12.3
4.5	16	2.4	13.6
4.6	10.5	2.1	8.4
5.2	10	4	6
7.4	10.6	5.7	4.9
8.1	8.6	4	4.6
9.4	8.15	5.2	2.95
9.5	8.4	0.85	7.55
11.2	5.1	0.2	4.9
11.3	7.3	0.4	6.9
11.4	10.25	0.4	9.85
12.4	7.2	1.45	5.75

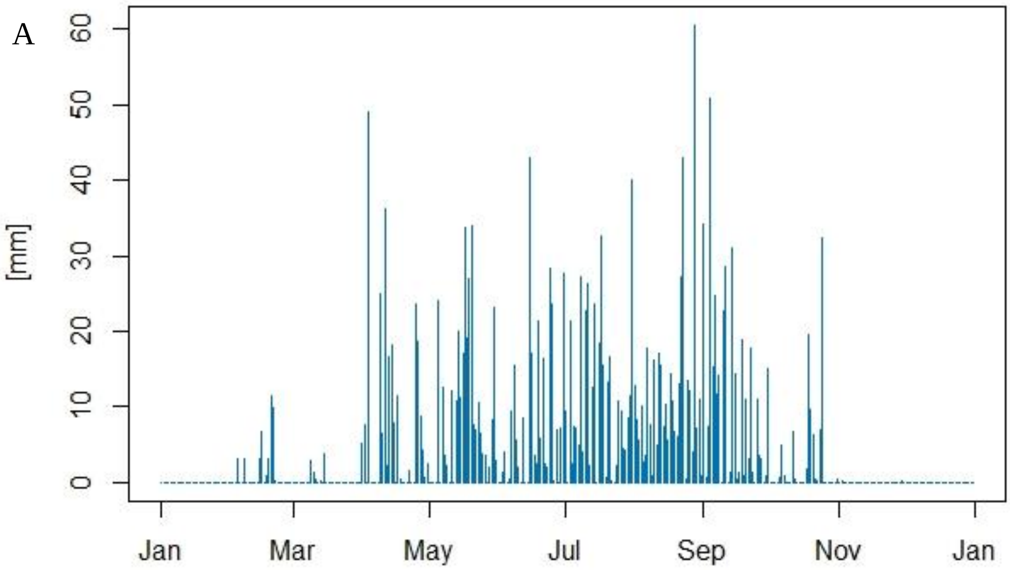
In general, the distances from ground surface to the water levels in the wells are greater in the end of the dry season and smallest in the end of the rain season (Table A3).

Table A3. Percentage of when the wells have their deepest and shallowest distance to ground surface for Dangishta and Robit Bata watershed in 2017 respectively. Note that there were no water level measurements in August for Dangihta watershed. The first column for Robita Bata exceeds 100% due to the deepest distance for one specific well occurred twice

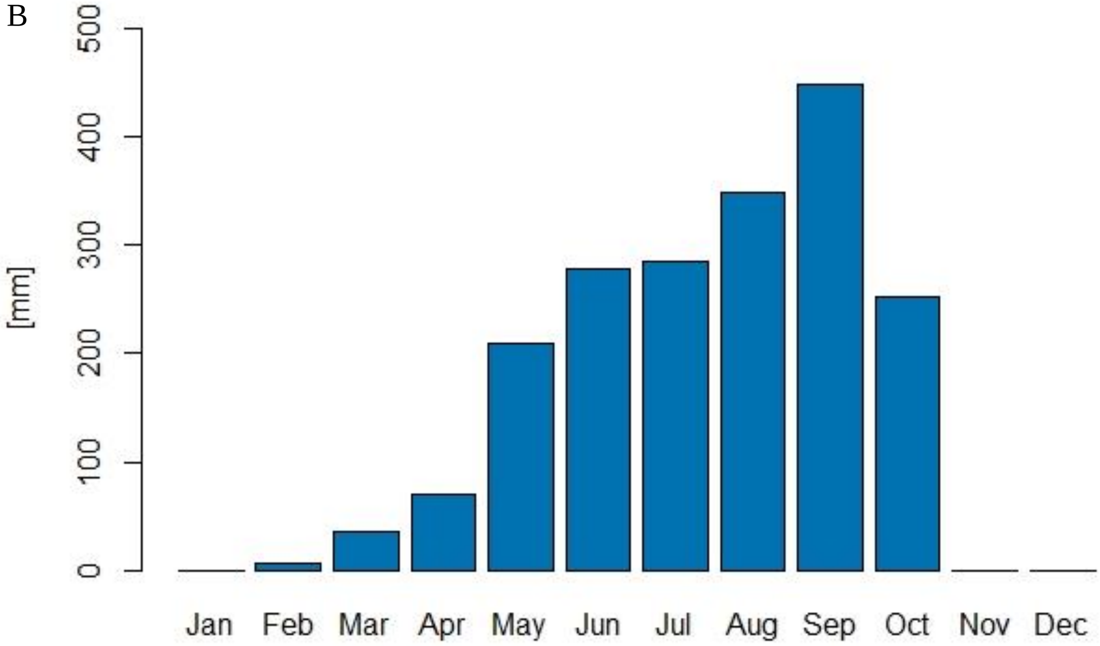
	DANGISHTA		ROBIT BATA	
	% Deepest distance occurs	% Shallowest distance occurs	% Deepest distance occurs	% Shallowest distance occurs
Jan	13.3	20.0	17.39	4.35
Feb	13.3	6.7	0.00	4.35
Mar	0.0	0.0	21.74	0.00
Apr	0.0	6.7	26.09	0.00
May	66.7	0.0	26.09	0.00
Jun	0.0	0.0	8.70	0.00
Jul	6.7	6.7	8.70	0.00
Aug	-	-	0.00	56.52
Sep	0.0	46.7	0.00	17.39
Oct	0.0	6.7	0.00	8.70
Nov	0.0	0.0	0.00	4.35
Dec	0.0	6.7	0.00	4.35

B. RAIN DATA

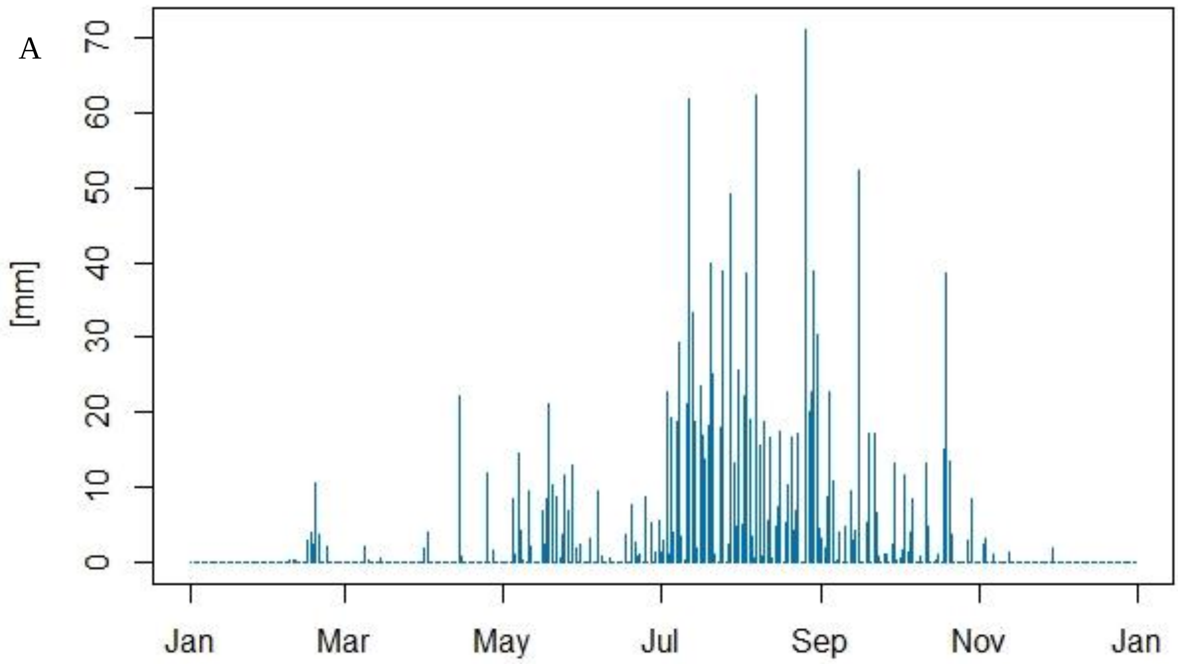
A

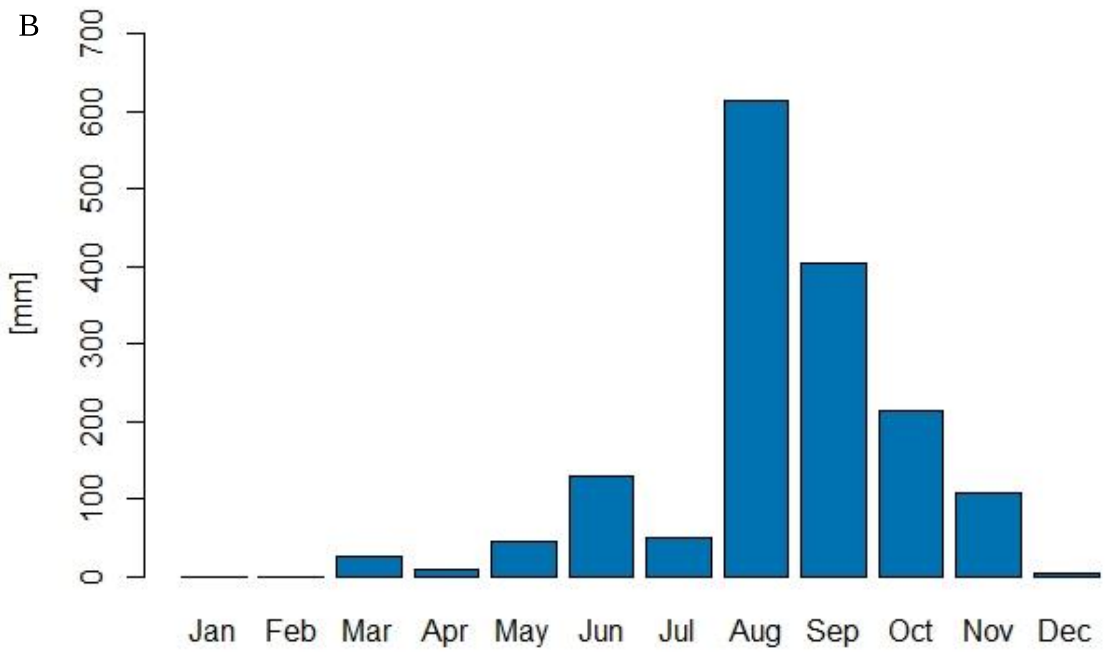


B



B1. A) Daily rainfall at National Meteorology Agency's station in Dangila year 2017 used for Dangishta watershed. B) Monthly rainfall at National Meteorology Agency's station in Dangila year 2017 used for Dangishta watershed.





B2. A) Daily rainfall at National Meteorology Agency's station in Bahir Dar year 2017 used for Robit Bata watershed. B) Monthly rainfall at National Meteorology Agency's station in Bahir Dar year 2017 used for Robit Bata watershed.

C. EXCEEDANCE OF WHO GUIDELINE

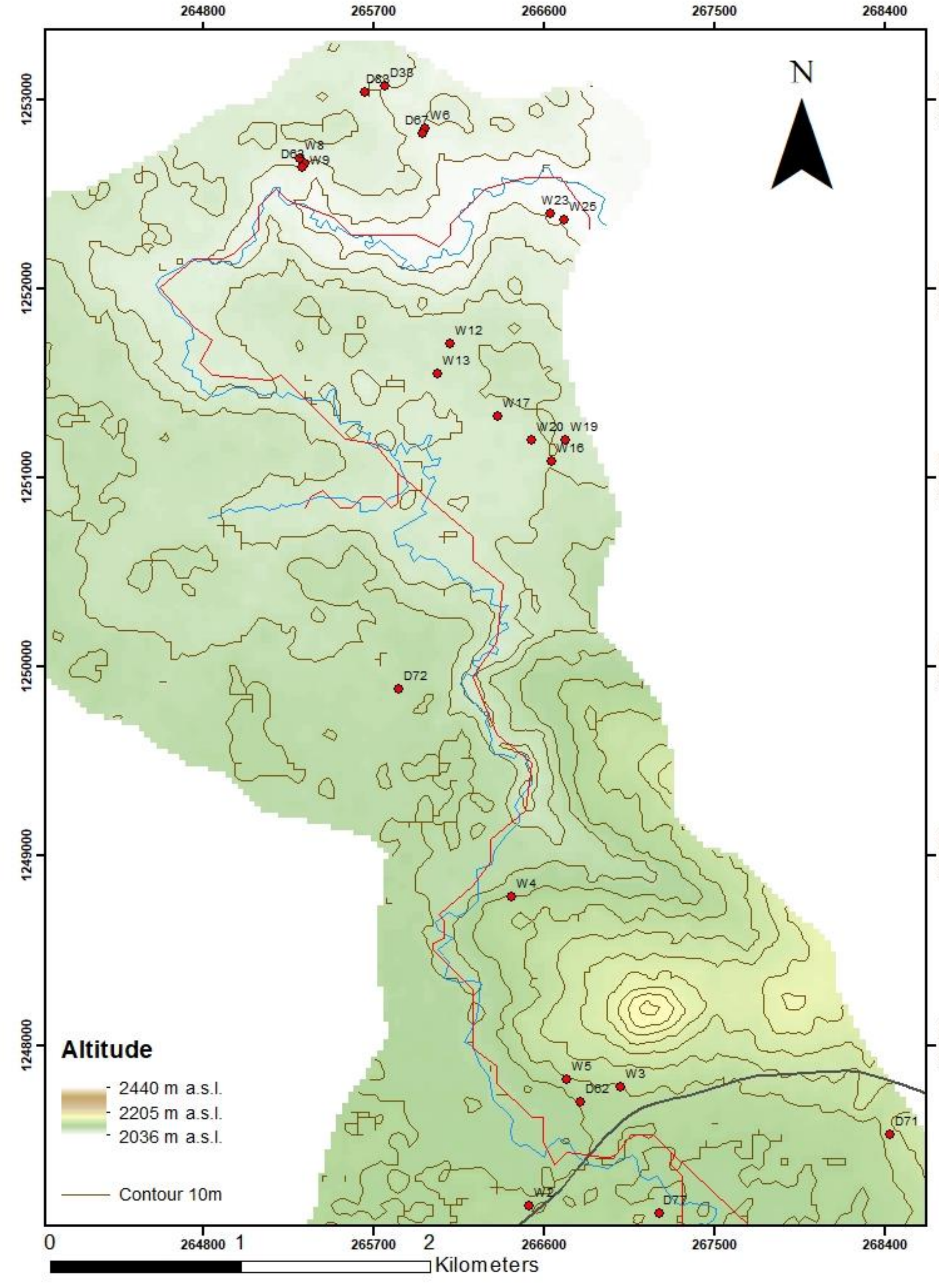
Table C1. Number of WHO guideline nitrate-N exceedance for Dangishta watershed (n=23)

Month	Number of Exceedances
Jan	0
Feb	0
Mar	0
Apr	0
May	0
Jun	1
Jul	7
Aug	3
Sep	7
Oct	2
Nov	3
Dec	5

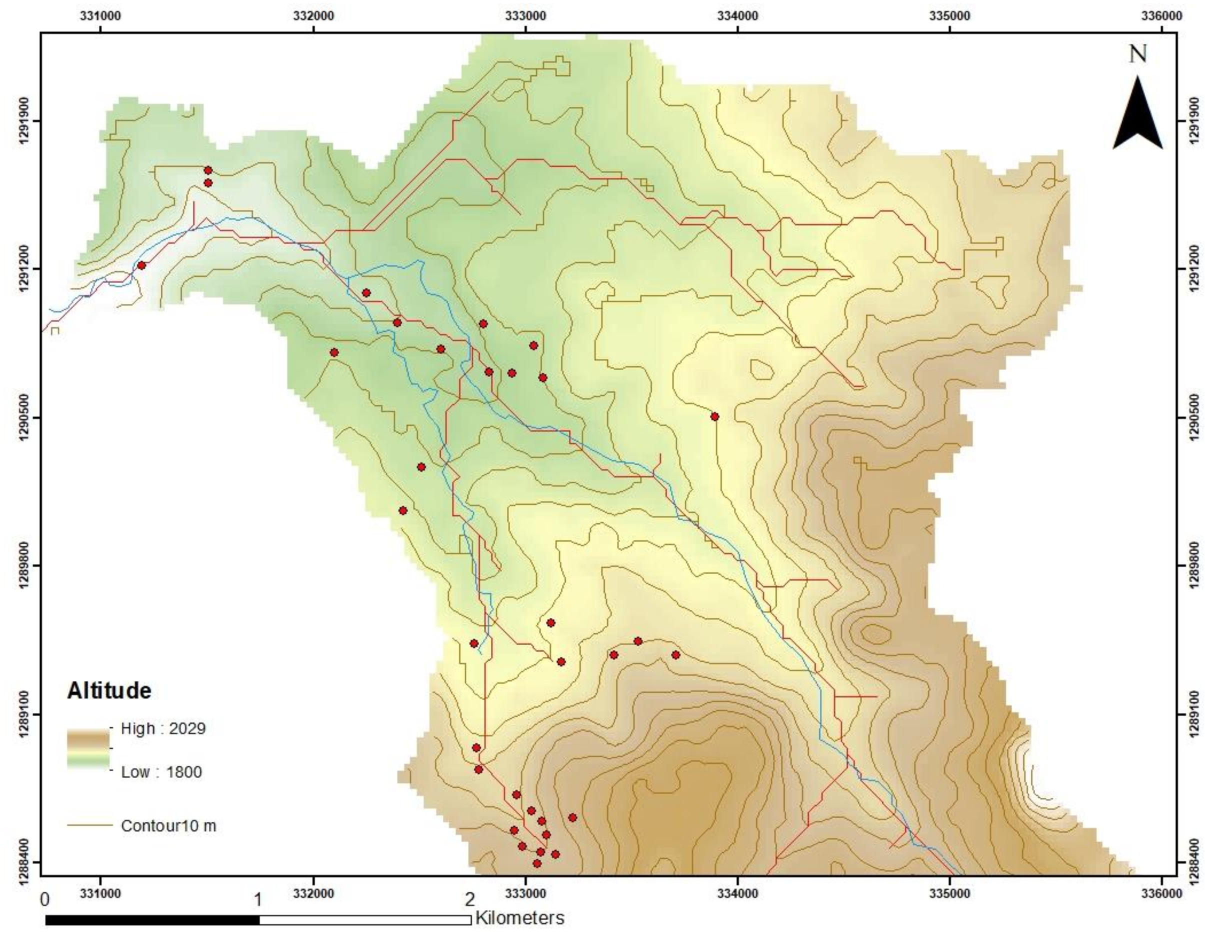
Table C2. Number of WHO guideline nitrate-N exceedance for Robit Bata watershed (n=33)

Month	Number of Exceedances
Jan	0
Feb	0
Mar	0
Apr	0
May	0
Jun	1
Jul	5
Aug	0
Sep	0
Oct	0
Nov	5
Dec	0

D. STREAMS AND DRAINAGE LINES



D1. Drainage lines (red) and river (blue) in Dangishta watershed.



D2. Drainage lines (red) and river (blue) in Robit Bata watershed.

E. PICTURES OF WELLS

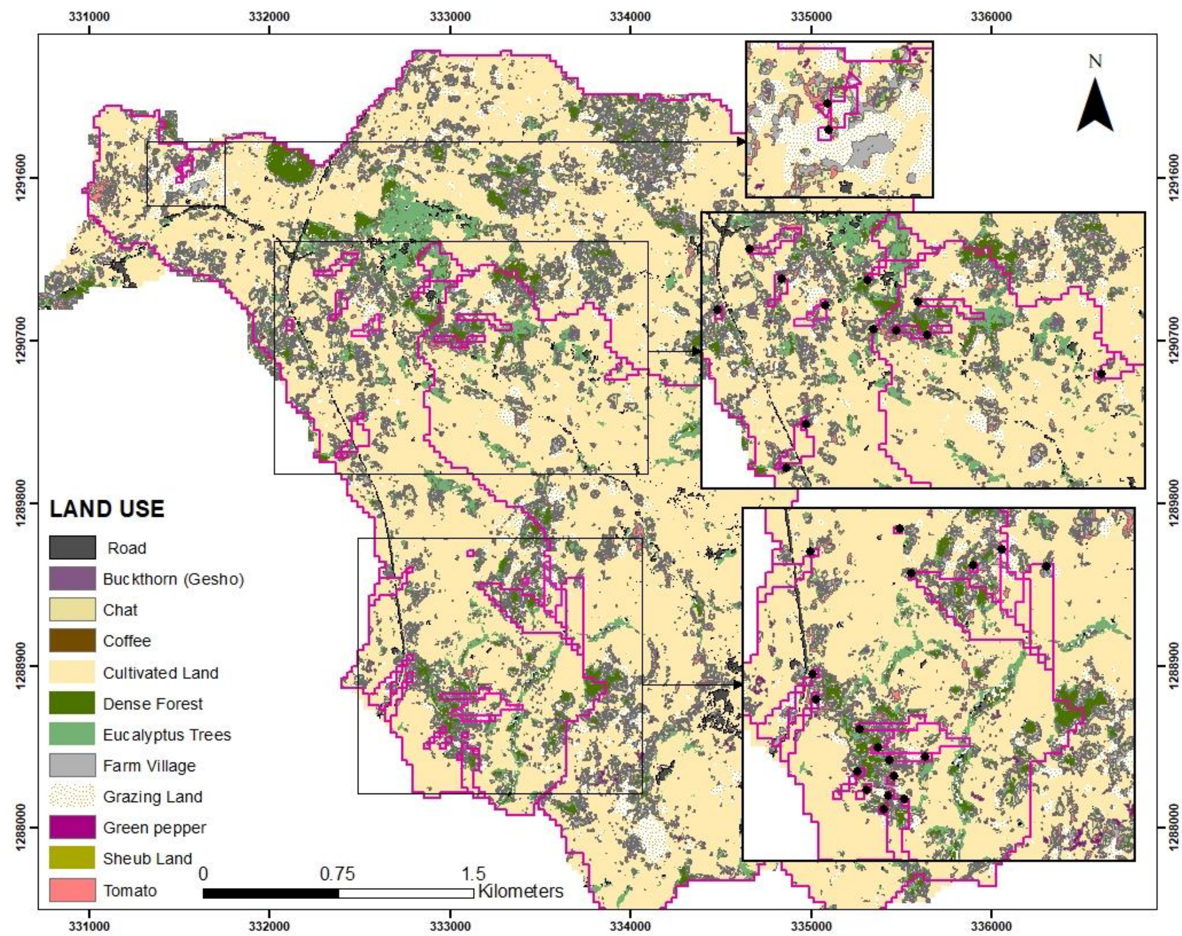
A

B

C

E1. A) A well with its lid laying next to it. B) A well without a lid. C) A well with lid and buckets used for storing water extracted from the well (Larsson 2018).

F. LAND USE MAP OF ROBIT BATA



F1. Land use map for Robit Bata developed by Yehulaie (2019). Drainage area are marked with pink outlines and wells with black dots.