Gully-Landslide interactions: an ecogeomorphic investigation

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Gully-landslide interactions: an ecogeomorphic investigation

by

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Dedication

To my parents, Cyprian and Joy, though you’re not here to read this, I know you’re watching and smiling at me and Vivian from above.

Abstract

Gully erosion and landsliding are important geomorphic processes that shape the Earth's surface, yet they pose significant hazards. Gully-induced landslides occur due to extreme gullying creating favourable conditions (e.g. bare and irregular surfaces) for expansion of already existing gullies (landslide-induced gully expansion). These gully-landslide feedbacks are facilitated by interactions among ecogeomorphic factors, yet little is known about the mechanism of these interactions. The aim of this study is to improve understanding of ecogeomorphic processes of gully-landslide interactions using examples from Southeast Nigeria. To achieve this aim, multi-method research methods were adopted: analysis of remotely sensed data, geotechnical investigations, quantitative and qualitative techniques and hydrological modelling. Gullies were mapped using high resolution data (0.61 – 5 m) acquired between November 2009 and December 2018 while supervised land-use classification was undertaken for both years. Geomorphic variables were acquired from the 30 m SRTM-DEM. Geotechnical investigations were conducted by Loraj Consortium, a partner of the Nigeria Environment and Watershed Management Project (NEWMAP) and results were made available for this research. Multiple regression analyses were used to establish associations between gully drivers and changes in gully sizes. Two focus group meetings were held and 192 copies of a questionnaire were distributed. The Soil and Water Assessment Tool model was used to understand effects of land-use changes on catchment hydrology and relate these changes with changes in gully sizes.

Results showed that major land-use changes, especially, reduction in fallow-cover, were recorded during the study period and interactions among ecogeomorphic factors were found to be significantly associated with changes in gully sizes. The soils in the study area are mainly sandy with low cohesion values which predispose them to dispersion by surface runoff and high seepage erosion. Modelling results showed there have been increased volumes of surface runoff between 2009 and 2018 due to increased non-vegetated surfaces, a view supported by focus group meeting attendees. Twenty six gullies covering an area of 0.36 km^2 were mapped in 2009 but in 2018, 39 gullies occupying 0.62 km^2 were mapped. Also, modelling results indicated that despite similarities in soils and geomorphology, hydrological responses of gully catchments varied, thus pointing to the uniqueness of catchments and possible variations in driving processes of individual gullies. Results from focus group meetings indicated there were no gullies in the area before the Nigerian civil war that lasted between 1967 and 1970. Military activities including digging trenches were said to have led to the initiation of the oldest gully

in 1968. Participants at focus group meeting said a lag existed between rainfall events and occurrence of gully-induced landslides, suggestive of effects of cumulative rainfall and groundwater as drivers of gullying. At visited gullies, presence of springs was observed suggestive of groundwater-driven gullying. Modelling results suggested high sub-surface flow in the study area, thus, fieldwork, focus group meetings and hydrological modelling all suggest that sub-surface flow is a potential driver of gullying in the study area. It has been suggested that in the design of gully-control, different gully catchments should be treated individually as no two catchments are the same. The multi-method research approach adopted in this research was helpful to understand gully-landslide interactions considering potential effects of ecogeomorphic processes. Adopting this research approach in future studies, especially in data-scarce regions, will improve understanding of geomorphic process in those regions and thus enhance design of management measures.

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Chapter 1

Introduction

1.0 Background to the study

Gully erosion and landsliding are geomorphic processes that contribute to landscape evolution (Goudie, 1990; Temesgen et al. 2001) yet they become hazardous when they interact with human activities. A gully is a relatively permanent, steep-sided water course which experiences ephemeral flows during a rainstorm (Morgan, 2009) and is formed when runoff accumulates and often recurs in narrow channels and, over short periods, erodes the soil from this narrow area to considerable depths (Poesen et al. 2003). Landslide is a general term for all varieties of mass movement on slopes (Varnes, 1984). The process of landsliding is restricted to hillslopes and always delivers loose materials to lower slopes (van Beek et al. 2008). Some landslides occur as a result of extreme gullying and they are referred to as gully-induced landslides. Landslides create bare and irregular surfaces which encourage concentration of runoff, thus, increasing runoff erosivity and subsequent initiation of new gullies, or expansion of existing gullies thereby resulting in landslide-induced gullying (Johnson & Warburton, 2015; Gómez-Gutiérrez et al. 2015). This feedback between gully-induced landslides and landslide-induced gullies creates complex gully landforms that pose challenges to gully management in many parts of the world (Betts et al. 2003; Osadebe et al. 2014; Igwe, 2015). Driving factors of gully erosion and landsliding have been studied and documented. There is a consensus among researchers that change in land use, especially, increase in bare and paved surfaces which increase flashiness and volume of surface runoff is the primary driver of gully erosion while extreme rainfall is often identified as a trigger factor of landsliding (section 2.2).

Gully erosion has significant effects on the availability of land for cultivation, crop productivity and land degradation (Morgan & Rickson, 1995; Zhang et al. 2002; Rickson et al. 2015; Graves et al. 2015) while landslides account for significant amounts of property damage (Igwe, 2012). Gully erosion and gully-induced landsliding are the dominant environmental problems in the southeast region of Nigeria. These associated problems have led to the isolation of villages, severance of communication lines such as roads, as well as loss of homes, schools, human and material resources worth several millions of dollars (Egboka et al. 1990). The earliest study on gully erosion in southeast Nigeria was documented in 1938 (Stamp, 1938) and over successive years, numerous researchers have studied the mechanisms of gully evolution. Different conceptual models of soil erosion have been developed to understand driving factors and more importantly, to design control measures to manage gullying (Egboka and Orajaka, 1987; Egboka et al. 1990; Gobin et al. 1999; Ezezika & Adetona, 2011). Despite the findings of these studies and implementation of various erosion-control measures, gully erosion is still endemic with the formation of new gullies and high headward retreat rates of existing ones (up to 60 m yr^{-1} in places, Hudec et al. 2005). This situation signifies the need for further understanding of the complex interactions between the different factors and actors influencing erosion at different scales (local and regional) and levels (Gobin et al. 1999). A better understanding of these interactions would enhance scientific knowledge of processes, aid the design of appropriate control measures and reduce associated hazards of gullying.

The relationship between gully erosion and landsliding has already been established (Bergonse and Reis 2016; Osadebe et al. 2014), for example, gully erosion has been identified as a preparatory factor for landsliding (Igwe, 2015), and landsliding has been suggested as a driver of gully erosion (Betts et al. 2003). Both geomorphic processes respond to land-use changes, especially, removal of forest cover as vegetation is thought to influence gullying and landsliding (Greenway, 1987; Stokes et al. 2008a; Stokes et al. 2008b). From the forgoing, it is evident that human-vegetation interactions (manifest in vegetal cover removal or planting) are significant in the study of gully erosion and landslides (Cooke & Reeves, 1976; Ghestem et al. 2011; Akpan et al. 2015). Therefore, in the study of the interactions between gully erosion and landsliding, it is imperative to adopt an approach that includes human-vegetation linkages at different scales (catchment and regional).

1.1 Ecogeomorphic perspectives

Ecogeomorphology refers to the discipline that studies the coupled evolution of geomorphological and ecosystem structures (Fagherazzi et al. 2004). Relationships between ecological and geomorphic processes are known (e.g. Viles, 1988a,b; Fantucci & Sorriso-Valvo, 1999; Stallins, 2006; Corenblit et al. 2011; Jones, 2012), while some authors adopted the term biogeomorphology to refer to the interface between ecology and geomorphology; other papers covering such interface do not explicitly discuss that they are ‘biogeomorphological’ in nature (Naylor et al. 2002). A review of papers on biogeomorphology reveals that they focus mainly on non-human elements of an environment and their relationship with geomorphic processes (e.g. Imeson, 1976; Voslamber & Veen, 1985; Corenblit et al. 2011, Viles, 2020). In order not to confuse the reader into thinking that the focus of this work is on the roles of non-human actors in influencing geomorphic processes and considering that humans as ecosystem engineers have affected gullying over time, ecogeomorphology is adopted over biogeomorphology in this work. For this study, ecogeomorphology is defined as the study of interactions between geomorphic and ecological (human-vegetation interactions) processes within an environment.

Human-vegetation interactions form the principal ecological drivers which modify landforms and affect gully erosion and landsliding (Guthrie 2002; Castillo et al. 2016). The deforestation activities of people expose bare soils to compaction and erosive runoff thereby producing gullies as resultant landforms; also, demographic pressure caused by population increase predisposes soils to gully erosion. Further gully evolution can result in steepening of slope angles, slope undercutting and removal of toe support, thus increasing susceptibility to failure (Igwe & Fukuoka, 2010; Igwe. et al. 2014; Maduka et al. 2017). Engineering construction on marginally stable slopes, toe undercutting during construction activities, as well as forest clearing, and logging can reactivate ancient landslides or predispose slopes to landslides. Consequently, bare surfaces created by 'human-induced' landslides increase susceptibility to gully erosion. Conversely, geomorphic processes affect tree growth, vegetation distribution (Parker & Bendix, 1996; Stallins, 2006) and agricultural activities, thus establishing a nexus of ecogeomorphic interrelationships which has not been fully studied and necessitating the need for improved understanding of dynamic feedbacks between ecological and geomorphic processes – this is the justification for adopting an ecogeomorphic investigation in this study. Wainwright & Parsons (2010) observed that there is a need to understand the dynamic feedbacks and interactions between ecological and geomorphic processes. Fulfilling this need will facilitate scientific understanding of interactions between processes that modify landforms. With reference to gully-landslide linkages; this improved understanding will provide a detailed appreciation of linkages which have far reaching effects on the environment, food production, housing as well as safety of affected population. By so doing, improvement in understanding of known processes of interactions would be achieved while management and mitigation of hazards accruing from these feedbacks will be improved, thus reducing associated risks.

1.2 Aim

This work therefore aims to study ecogeomorphic processes of gully-landslide interactions using examples from Southeast Nigeria. Fulfilling this aim will improve understanding of processes and inform management practices to reduce effects of gully-landslide interactions.

Chapter 2 presents background context and literature review leading to the development of a conceptual model of gully-landslide interactions. Materials and methods are discussed in chapter 3. Chapter 4 illustrates the effects of land use and land-use changes on gully characteristics while chapter 5 presents results on the influence of land-use changes on gully catchment hydrology. In chapter 6, findings on gully-landslide interactions are shown and discussed while chapter 7 discusses results on hazards and effects of these interactions. A synthesis of results is discussed in chapter 8 while a revised conceptual model which presents the key findings of this work is also shown. Conclusions and suggestions for future work follow in chapter 9.

Chapter 2

Background context

2.0 Introduction

Chapter 2 establishes the research context related to the present study. Mechanisms of gully development and landsliding are reviewed in section 2.1 while section 2.2 discusses drivers of gullying and landsliding. A conceptual model of gully-landslide interactions based on reviewed literature, established gaps and research questions are discussed in section 2.3.

2.1 Mechanisms of gully development and landsliding

Gully erosion can result from different mechanisms including subsurface mechanisms (e.g. piping and seepage erosion), and surface mechanisms (for instance fluting, incision by rainfall and surface runoff, development of rills and landsliding) (Dunne, 1990; Betts et al. 2003; Gómez-Gutiérrez et al. 2015; Bernatek-Jakiel & Poesen, 2018). Sub-surface erosion of soil particles can occur through seepage erosion (Dunne, 1990), actions of lateral movement of water within the soil (Berry, 1970), groundwater driven erosion (Okagbue & Uma, 1987) as well as piping (Bernatek-Jakiel & Poesen, 2018). Events that channel surface runoff underground, e.g. increase in biogeomorphic activities such as animal burrows will likely propagate sub-surface erosion (Swanson et al, 1989; Chappell, 2010).

Piping refers to subsurface concentrated flow erosion due to bypass flow and it is controlled by factors such as soil characteristics at depth, particularly the presence of differential porosity, solubility and strength (Vanmaercke et al. 2016). Collapse of pipe-roofs leads to gully formation. Piping as a mechanism of gully erosion has been recorded in almost all climatic regions of the world (Bernatek-Jakiel & Poesen, 2018). Seepage erosion is the entrainment of soil or rock resulting from water flowing through and emerging from a porous medium and may involve individual grains or large masses of soil or fractured rock (Dunne, 1990). High sand content and high infiltration capacity make soils susceptible to seepage erosion (Okagbue & Ezechi, 1988). Two processes of seepage erosion have been identified: (1) through the development of a critical body force or drag force that entrains particles in water seeping through and out of a porous medium causing either liquefaction or Coulomb failure: and (2) through the application of a shear stress to the margins of a macropore which may have originated independently of the water flow (Dunne, 1990). While the first mechanism is thought to be dominant in loose/non-cohesive materials, the latter is found in consolidated soils (Dunne, 1990; Beven & Germann, 2013).

Flutes are vertically elongated grooves, generally tapering towards the top that furrow into the wall of the gully and result predominantly from the action of flowing water or throughflow (Vandekerckhove et al. 2000; Poesen et al. 2002). In the deeply weathered tropical soils of southeast Nigeria, incisions by rainfall, gully headcut retreat and lateral expansion due to landsliding as well as development of rills are thought to be major mechanisms driving gully development (Okagbue & Uma, 1987; Osadebe et al. 2014). Incision driven by rainfall and surface runoff can be facilitated by removal of vegetation, road construction and irregularities in surface configuration created by landslide scars or tectonic activities and saturation overland flow (Egboka et al. 1990; Ayele et al. 2018), whereas development of rills can result from improper land uses especially poor agricultural practices (Osuji, 1984).

Gully expansion by landsliding can occur in two ways:

i. Landslides can create bare surfaces by removing vegetation while irregular surfaces shaped by landslide scars encourage runoff concentration and enhance runoff erosivity (Johnson & Warburton, 2015; Gómez-Gutiérrez et al. 2015).
ii. Landsliding could become the dominant process of gully head formation through processes such as slumping due to the removal of toe support by running water or human activities (Torri & Poesen 2014).

Four stages of gully evolution have been identified: formation of rills, development of incipient gullies, formation of shallow gullies (< 15 m deep), and development of deep gullies (> 15 m deep), (Okagbue & Uma, 1987). During the first three stages of gully development, surface erosion and fluvial incision are the primary methods of gully expansion and the role of landsliding as a gully-driver is of little significance (except when gully erosion is triggered by landslides). However, as a gully passes a critical threshold of sidewall length and/or slope in their final stages of evolution, sidewalls begin to fail and landsliding associated with groundwater fluxes is thought to become the dominant gully-driver (Okagbue & Uma, 1987; Betts et al. 2003). Groundwater control is evidenced in the presence of springs at several horizons of the gullies (Okagbue & Uma, 1987).

Landslides are thought to be of hydrometeorologic as well as seismic origins and are common geological hazards in areas where the slope angle of soils and regoliths over bedrock is greater than its frictional angle (Akpan et al. 2015). Susceptibility of slopes to landslides is usually expressed in terms of *factor of safety*, F, (Equation 2.1) where

$$F = \frac{sum\ of\ resisting\ forces}{sum\ of\ driving\ forces} \qquad Eq.\ 2.1$$

Where $F < 1$ the slope is in a condition for failure, where $F > 1$ the slope is likely to be stable and where the forces promoting stability are exactly equal to the forces promoting instability, $F = 1$ (Selby, 1993). Different classifications of landslides exist in the literature, e.g. Varnes (1978) and Hutchinson (1968). Shallow translational slides are common in southeast Nigeria, especially, in areas where toe support has been removed by gully erosion or where gully erosion increases slope angle by continuous removal of slope materials and thus increasing propensity to gully-induced landsliding (Igwe & Fukuoka, 2010; Igwe et al. 2014; Maduka et al. 2017). While general driving factors responsible for landsliding are reviewed in this chapter and other types of landslides may be mentioned for wider context, this study is focused on gully-induced landslides.

2.2 Drivers of gullying and landsliding

Several drivers of gully erosion and landsliding have been reported in different environments (Table 2.1). Discussions of these factors are presented in turn in the following sub-sections.

Table 2.1: Example references of factors that affect initiation and development of gullies and landslides. Landslides create favourable conditions for gully erosion, while gully erosion enhances landsliding, hence, both processes have been included in this table.

Driving factor	Study area	Reference
Climate		
• Rainfall	Nigeria Nigeria Nigeria Nigeria	Ofomata, (1987) Obi & Salako, (1995) Afegbua et al. (2016) Nwajide et al. (1988)
• Soil thawing and snowmelt runoff	Saskatchewan, Canada Romania Romania	Archibold et al. (2003) Ionita, (2006) Ionita et al. (2015)
• Temperature	Italy	Zanchi & Torri, (1980)
• Drought	Kenya Spain	Fleitmann et al. (2007) Cerdà, (1997)
Geology		
• Hydrogeological and geotechnical	Nigeria	Egboka and Nwankwor, (1985) Egboka et al. (1990) Afegbua et al. (2016)
• Palaeo and neo-tectonics		
• Underlying geology	Nigeria	
• Lithology	Italy Italy Turkey	Conforti et al. (2011) Guzzetti et al. (1996) Akgün & Türk, (2011) Igwe (2015a)

• Inter-bedding • Faults, discontinuities and lineaments	Nigeria India Nigeria Nigeria Nigeria Italy Argentina	Mishra et al. (2018) Igwe et al. (2014) Akpan et al. (2015) Maduka et al. (2017) Ietto et al. (2007) Sanchez et al. (2010)
Ecological drivers • Land cover and soil management • Deforestation, logging and land-use change • Unsound farming practises/reduction in conservation techniques • Engineering construction • Unplanned settlement • Intensified land use	Ethiopia DR Congo DR Congo Nigeria Nigeria – Canada Canada Australia Nigeria EU Iran Iran China China Turkey – Ethiopia	Nyssen et al. (2010) Imwangana, et. al. (2014) Moeyersons, et. al. (2015) Stamp, (1938), Steel, et al. (1951), Fanciullacci, (1978) Poesen et al. (2003) Rood (1984) Guthrie (2002) Blong and Dunkerley (1976) Osuji, (1984) Panagos et al, (2020) Rahmati et al. (2017) Zabihi et al. (2018) Xie & Qu (2018) Wang et al. (2018) Demir, (2018) Guerra et al. (2017) Lemma et al. (2019)
Soil characteristics • Soil structure • Antecedent soil moisture • Degree of weathering • Clay content • Soil moisture	Nigeria Tennessee, United States Zimbabwe Central Kansas, USA Nigeria Nigeria – Hong Kong Norway Japan Spain Turkey Uganda	Idowu & Oluwatosin (2008) Luffman et al. (2015) Stocking, (1980) Karimov et al. (2015) Emeh & Igwe 2017 Igwe (2014) Veder (1981) So (1976) Okamoto et al, (2004), Shuzui (2001) Azañón et al (2010) Yalcin, (2007) Broeckx et al (2019)

Topography		
• Topography	Mediterranean (Italy and Spain) Nigeria	Gómez-Gutiérrez et al. (2015). Iheme et al. (2016).
• Slope angle	Turkey South Africa Uganda Guatemala Japan USA South Korea	Akgün & Türk (2011) Le Roux & Sumner (2012) Broeckx et al (2019) Coe et al. (2004) Aniya (1985) Parise & Jibson (2000) Lee and Min, (2001)
• Slope aspect	China USA Japan	Lan et al. (2004) Churchill (1982) Aniya (1985)
• Landslides	England Nigeria Mediterranean (Italy and Spain)	Johnson & Warburton, (2015) Osadebe et al. (2014), Osadebe & Akpokodje (2007) Gómez-Gutiérrez et al. (2015)
• Gully erosion	New Zealand Nigeria Nigeria	Betts et al. (2003) Igwe et al. (2014) Effiong et al. (2015)
• Earthquake	Uganda Hong Kong Nepal China	Ngecu et al. (2004) Zhou et al. (2002) Rosser et al. (2021) Parker et al. (2011)

2.2.1 Climatic factors

The importance of excessive rainfall, rainfall intensity and rainfall erosivity in gully erosion is widely recognised (e.g. Ofomata, 1987; Obi & Salako, 1995; Afegbua et al. 2016; Vanmaercke et al. 2016). Precipitation duration and accumulation (including antecedent precipitation accumulation) were found to be significant in initiating and propagating erosion in the humid subtropical climate of the United States (Luffman et al. 2015). The significance of this study by Luffman et al (2015) relates to reduction in soil cohesion by antecedent rain thereby making such soil particles more susceptible to entrainment, as well as effect of antecedent rains on soil saturation. Saturated soils support surface runoff and surface runoff is a primary driver of gully erosion, especially, at the initial stages of gully evolution (Poesen et al. 2003; Betts et al. 2003). The observation of Luffman et al (2015) slightly differs from those of Ofomata (1987) who identified rainfall intensity as a principal factor in gully initiation in the humid tropics.

Air temperature can be a good proxy for rainfall erosivity and runoff production (Zanchi & Torri, 1980; Vanmaercke et al. 2016). The point being made here is important for two reasons: First, temperature is an important factor in soil weathering (Brady et al. 1999). Deeply weathered soils are susceptible to landsliding (Igwe, 2014) because an increase in the depth of weathered regolith presents sufficient slope materials available for slope failure. Landslides create bare surfaces by removing vegetation, thus increasing susceptibility to gully erosion. Secondly, increase in temperature increases rate of evaporation (Barry, 1971) which could affect convectional rainstorms. These storms when armed with sufficient kinetic energy can erode soils and enhance soil erosion. Therefore, climatic factors (especially rainfall and temperature) can influence gully-landslide interactions directly through soil erosion by direct raindrop impact and availability of surface runoff, as well as indirectly through interactions with soil properties such as degree of weathering by providing both moisture and temperature.

Prolonged drought leads to desiccation of soils thus increasing susceptibility to erosion (Cerdà, 1997; Fleitmann et al. 2007). Drought can increase susceptibility to soil erosion in two ways: First by reducing infiltration capacity of soils. This reduction is brought about by effective sealing of soil surfaces as a result of dryness (Ibbitt et al. 1997). Secondly, prolonged dryness reduces vegetation cover within an environment thereby producing bare soils which are attacked by runoff and in turn produce gullies as resultant landforms via the mechanism described in section 2.1. Soil thawing and snowmelt can cause soil erosion in colder environments (Zhang et al. 2007). As soils thaw and packed snow melts, two processes are likely to bring about erosion. First, soil thawing which means soil particles are less-consolidated and cohesive as they once were, thereby making it easier for runoff entrainment; less-cohesive and less-consolidated materials are more susceptible to erosion (Kamphuis & Hall, 1983; Frankl et al, 2021). Secondly, as snow melts, surface runoff gains more velocity due to availability of more water to flow on the surface.

Regarding landsliding, extreme rainfall can have many effects on slope materials which affect hillslope hydrology. First, by enhancing pore-water pressure , secondly, extreme rainfall can increase the level of saturation of regolith thereby reducing shear strength of slope materials (Larsson 1989). Thirdly, water can cause clay hydration, weight of rainwater can add to surcharge, water is an agent of weathering and finally, water can increase seepage pressure (Selby, 1993). Pore-water can reduce shear resistance of regolith, as shown in the shear equation (Equation 2.2):

$$S = c + (p - h_{\gamma w})\tan \phi \qquad \textit{Eq. 2.2}$$

where S = shearing resistance per unit area
c = cohesion per unit area (kN/m^2)
p = pressure due to the weight of solids and water (kN/m^3)
h = piezometric head
γ_w = unit weight of water (kN/m^3)
ϕ = angle of internal friction (°)

Increase in the piezometric head reduces the friction component (p - $h\gamma_w$) tan ϕ as well as cohesion, thus resulting in substantial reduction in shear resistance of regolith and subsequent susceptibility to sliding (Nwajide et al. 1988). Rainfall, a climatic driver of landsliding, interacts with other physical factors e.g. geology (inter-bedding of permeable and non-permeable slope materials) and physical properties of the soils (clay content) to increase susceptibility to slope failure. Where there is inter-bedding of more permeable sandy soils and less permeable clay materials, clay hydration could lead to instability within a slope (Igwe, 2015b). Absorption of water and subsequent expansion of clay minerals may exert upward force on overlying sandy materials, subsequent drying, shrinkage and peeling off in large chunk of clay materials further creates instability in the sandy materials above. This cycle of swelling and shrinkage of clay materials over time can bring about slope failure (Igwe, 2015b). On a slope whose stability has been compromised by alternative swelling and shrinkage of clay materials, additional stress resultung from increase in self-weight caused by rainfall can ignite slope failure (Igwe, 2015b). Rainfall is a primary trigger of landsliding; however, most times rainfall only acts as a trigger mechanism of landslides on slopes that are already predisposed to failure by geologic, structural and geomorphic factors (Igwe et al. 2016).

2.2.2 Geology and lithology

The rate and nature of geomorphological processes are partially dependent on the lithology of the underlying materials (Dai et al. 2001). Sedimentary rocks are by far the most common lithological group affected by gully erosion, and this is most likely due to their frequently lower resistance to erosion (Castillo & Gómez, 2016). Globally, unconsolidated sandstones, mudstones and shales are often reported to show a high incidence of gully erosion (Betts et al. 2003; Sonneveld et al. 2005; Parkner et al. 2006; Ghimire et al. 2006; Nwilo et al. 2011;

Castillo & Gómez, 2016). In Nigeria, gully erosion has scarred the sedimentary basins of the southeast region, thus making gully erosion the dominant environment problem of the region (Ofomata, 1987; Egboka et al. 1990).

While sedimentary rocks may be susceptible to gullying, other local and regional factors such as hydrogeology and local tectonic events also affect gully erosion. For example, Egboka and Nwankwor (1985) suggested that the primary control of gully formation and development of the Agulu-Nanka gully complex in southeast Nigeria was the hydrogeological and geotechnical properties of complex aquifers of the gullies. Tectonic events can increase susceptibility to gully erosion and landsliding by creating favourable landforms such as natural cracks and cuestas which can be attacked by erosive agents (Egboka et al. 1990). For instance, southeast Nigeria has climatic and land-use characteristics which are very similar to those of southwest Nigeria, as well as being underlain by similar Tertiary formations. Despite these similarities, gully erosion and landslides are much less common in the latter and this situation has been linked to tectonic activities which provided suitable landforms (such as cuestas and cracks) that have been attacked by erosive forces in southeast Nigeria (Egboka et al. 1990).

Highly fractured rock materials are susceptible to gully erosion and landsliding (Akgün & Türk, 2011; Igwe, 2015b). Fractures and discontinuities can provide local access to weathering agents' (e.g. water) thereby increasing weathering penetration and depth of weathered materials available for landsliding; weathering can increase the rate of soils susceptibility to erosion and landslides (Emeh & Igwe, 2017). Natural fractures can be attacked by surface runoff which enhances development of gully erosion. Furthermore, fissures can increase rates of infiltration thereby increasing porewater pressure, a trigger factor of landsliding (Quinn et al. 2010). Lineaments and discontinuities can enhance landsliding (Igwe. et al. 2016), especially where they occur at the interface of permeable and impermeable materials.

Akpan et al. (2015) identified that inter-bedding of permeable units such as marl and impermeable units such as shale/clay could lead to slope instabilities, the significance of uneven permeability is explained. As rain falls, most downward percolating water would be blocked by underlying impermeable materials (Akpan et al. 2015). Thus, as blocked groundwater gradually accumulates at the interface of permeable and impermeable rocks, pore-pressure and uplift forces increase while cohesive forces reduce, leading to instability (Nwajide et al. 1988). With further increase in rainfall, the regolith becomes over-saturated thereby increasing instability conditions (Nwajide et al. 1988; Akpan et al. 2015). In gully channels where inter-bedded slope materials are exposed, slope failure maybe be facilitated by two processes, first, removal of toe support by gully bank undercutting. Evolution of gullies accompanied by prolonged wet conditions encourages gully bank undercutting by concentrated flow and subsequent occurrences of landslides (Ionita, et al. 2015; Goodwin et al. 2017). Secondly, increased pore water pressure resulting from perched aquifers at the exposed interface between permeable and non-permeable slope materials facilitates sliding by increasing shear stress on slope materials (Nwajide et al. 1988).

2.2.3 Topography

Topography is a key factor for the initiation and development of geomorphic processes because it influences the erosive power of the flow of surface runoff (Gómez-Gutiérrez et al. 2015; Yibeltal et al. 2019a). Thus, while rainfall is significant for gully initiation, topography can be considered an enabler of rainfall to bring about gully erosion. Topographic factors include slope aspect, slope length, slope angle, curvature, altitude and upslope contributing area. Slope aspect is an important factor with regards to microclimate and vegetation cover (Zabihi et al. 2018). South-facing slopes in the northern hemisphere are more susceptible to gully erosion than north-facing slopes (Rahmati et al. 2017) because the more arid conditions experienced on south-facing slopes likely support less vegetal protection from surface runoff (Armesto & Martínez, 1978). With regards to landslides, sun-shadow slopes have higher landslide events than slopes facing the sun due to the lower ground temperature, higher soil moisture and thicker residuum present in the shaded slopes (Lan et al. 2004).

A direct relationship exists between slope length and gully erosion locations – higher slope lengths increase surface runoff and so increase probability of gully erosion occurrence (Renard et al. 1997; Conforti et al. 2011; Zabihi et al. 2018). Parkner et al. (2006) identified gully erosion within the indigenous, undisturbed forest of the North Island of New Zealand on slopes of 40º and above. Conforti et al. (2011) recognised highest gully density on slopes >30º in Northern Italy. Zabihi et al (2018) suggested that slope angles >30º had greatest susceptibility to gully erosion in the Mazandaran Province, northern Iran. These studies contrast with those of Le Roux & Sumner (2012), Rahmati et al. (2017) and Yibeltal et al. (2019b) who observed that slope angles less than 10º and 15º had highest concentrations of gully erosion in the Eastern Cape Province of South Africa, the Kashkan-Poldokhtar Watershed of Iran and the Upper Nile Basin of Ethiopia respectively. In southeast Nigeria, Iro (2018) found a dominance (57%) of gullies on slopes between 10 – 20º. It is plausible that higher slopes were required for the formation of gullies in the north Island of New Zealand due to higher vegetation cover which has soil stabilizing effects. It is also possible that other factors such as land-use change played important roles in initiating gullies on lower-medium gradient slopes (10 – 20º) within the study areas covered by Le Roux & Sumner (2012), Rahmati et al. (2017) and Iro (2018). Infiltrated water in the high-slope sections could lead to lateral-flow erosion and gully expansion in the gentler-slope portions of the land (Tebebu et al. 2010; Yibeltal et al. 2019b). The concentration of surface runoff from cultivated farms in a watershed can enhance gully formation on gentler slopes of the watershed and finally, steeper slope angles which encourage concentration of runoff promote gully formation on the adjacent gentle-slope areas of the land (Sultan et al. 2018; Yibeltal et al. 2019b). These explanations are likely reasons higher gully concentrations have been reported on gentle slopes. While the identified studies reported gully concentrations and susceptibilities in certain slope classes, effects of interactions between slope angle and other gully-drivers such as land-use changes and nearness to rivers on changes in gully sizes (e.g. length or area) are not readily available. Ascertaining effects of gully-drivers on changes in gully sizes may be significant in the design of gully-management projects.

Concerning elevation, Iro (2018) studied 14 gullies in southeast Nigeria and found that all studied gullies occurred on elevations >10 m above sea level, while Zabihi et al (2018) observed an inverse association between gully erosion and elevation with highest Frequency Ratio for the elevation class of 1006 – 1220 m followed by 1220 – 1420 m. The area studied by Iro (2018) is relatively low-lying (-11 to 516 m) compared to that by Zabihi et al (2018) which ranged between 1006 – 1839 m. Curvature indicates the effect of local terrain morphometry on overland flow distribution and by extension, gully erosion (Shary et al. 2002: Zabihi et al. 2018). Both Zabihi et al (2018) and Iro (2018) observed dominance of gullies on concave slopes, thus suggesting that accumulation of runoff and subsequent high velocity could lead to gully erosion.

While it has been established that the size of gully upslope contributing area has a critical control on gullying as larger catchments produce higher volumes of runoff (Frankl et al. 2012; Dong et al. 2013; Vanmaercke et al. 2016; Yibeltal et al. 2019a), considering the influence of changes in land use on gully evolution (section 2.2.4), it is also important to understand how these land-use changes in individual gully catchments influence gullying. For example, gully evolution in a catchment dominated by forests will likely be driven by a different process than in a catchment dominated by non-vegetated surfaces. A better understanding of gully-driving processes in individual catchments aids design of appropriate gully-management projects (Yibeltal et al. 2019a).

Landsliding increases with slope angle attaining a maximum frequency of occurrence, normally between 30º and 40º, and having a sharp decline after 40º which has been attributed to the absence of debris for failure and to the highly unstable nature of such slopes (Dai & Lee, 2002; Gomez & Kavzoglu, 2005; Barlow et al. 2009). In southeast Nigeria, a strong positive correlation between slope gradient and landslide density was found (r = 0.85), while shallow translational slides and debris avalanche have been observed on slopes between 32 – 42º in same region (Igwe, 2014; Igwe et al. 2014; Emeh and Igwe, 2017). Gully erosion is known to increase slope angles by gradual removal of slope materials, and thus, enhancing gully-induced slope failure (Igwe & Fukuoka, 2010). In other parts of the world, landslides have been observed on different slope gradients ranging from 10º to 50º while other factors such as rainfall were suggested as trigger factors (Temesgen et al. 2001; Iida and Okunishi 1983). Reported results in this section imply that while topography is an important driver of geomorphic processes (e.g. landsliding and gully erosion), other forcing elements such as extreme rainfall, interact and initiate these geomorphic processes on a variety of topographic regimes; mechanism of erosion and landsliding vary depending on these interactions.

2.2.4 Deforestation and land-use changes

There is a consensus among researchers that human activities such as deforestation, land-use changes (especially changes that increase non-vegetated surfaces and reduce vegetal cover) and unsound farming practices such as cultivation on gully prone areas, worsen the problems of gully erosion (Stamp, 1938; Fanciullacci, 1978; Osuji, 1984; Osadebe & Akpokodje . 2007; Ezezika & Adetona, 2011; Ionita et al. 2015; Nwankwor et al. 2015; Zakerinejad & Maerker, 2015; Yibeltal et al. 2019b; Frankl et al. 2019; Panagos et al. 2020). In as much as physical factors such as cuesta landforms can increase susceptibility to gully erosion (Ofomata, 1987), these studies on deforestation suggest that human activities are the main drivers of gully evolution and have acted differently in time and occurs across different countries depending on the history of land use and management practices (Castillo et al. 2016). In southeast Nigeria for example, results from the earliest documented studies on soil erosion (Stamp, 1938) indicate that removal of vegetal cover influenced initiation of soil erosion, and subsequent studies until present are in agreement with the suggestions of Stamp (1938) regarding the effects of vegetal cover removal and gully evolution in the region (Njoku et al. 2017; Attah et al. 2013; Iro 2018).

The significance of deforestation in gully erosion studies derives from the fact that natural vegetation shields soils from direct impacts of rainfall, creates friction for surface runoff thereby retarding erosive power of surface runoff as well as protects the soil from direct compaction from humans and other grazing animals (Cooke & Reeves, 1976; Yibeltal et al. 2019). Deforestation has three implications (figure 2.1):

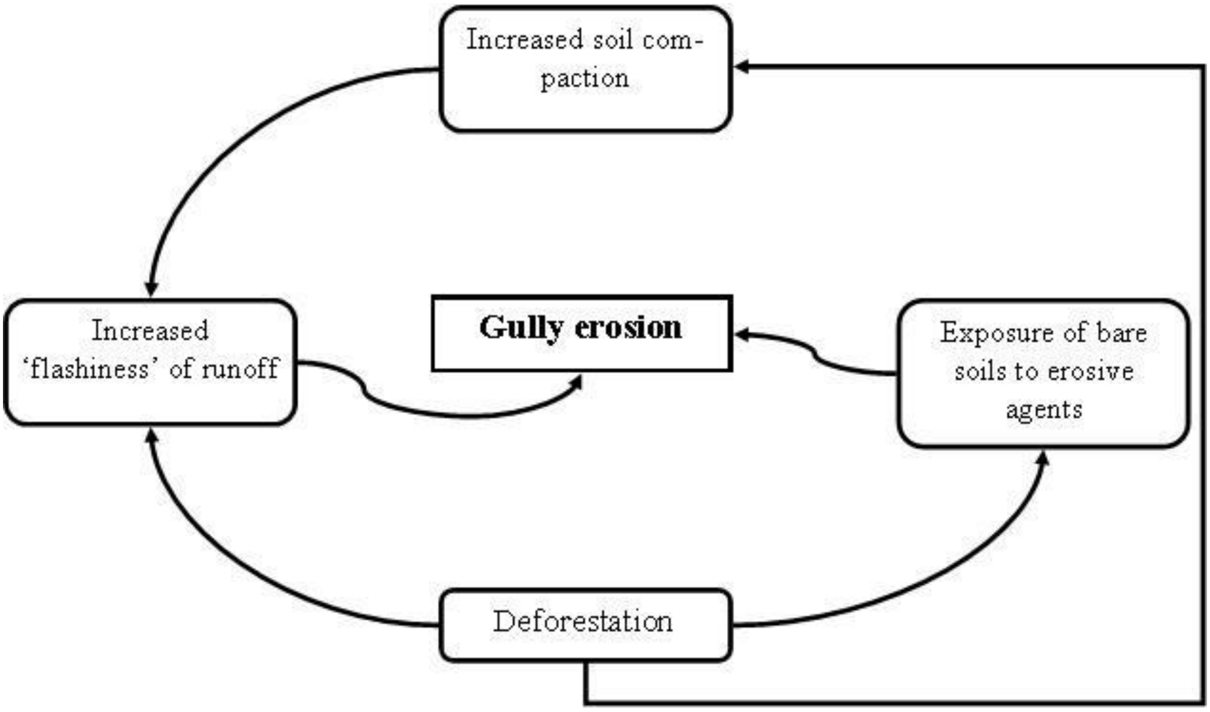


Figure 2.1: Deforestation, a human-induced driver of gully erosion

1. Exposure of bare soils to erosive runoff and rainfall impact.
2. Deforestation can lead to increased 'flashiness' and erosivity of runoff as a result of reduction in surface roughness.
3. Increased compaction of soils which in turn increases 'flashiness' and erosivity of runoff.

Regarding landslides, vegetation influences landsliding in two ways: hydrological and mechanical, and these two influences can have negative and positive impacts on landsliding (Table 2.2). Hydrological influences include interception and subsequent loss to evaporation of intercepted precipitation by vegetation, increase in roughness of ground surface by tree roots, thereby increasing infiltration capacity of soils, as well as extraction and loss through transpiration of soil moisture by plant roots (Greenway, 1987). However, evapotranspiration from trees might have a limited effect under a tropical precipitation regime, where soils are often saturated (Schwingshackl et al. 2017; Broeckx et al. 2019). Mechanical influences include transmission of dynamic forces into slopes (Greenway, 1987; Akpan et al 2015), increase in surcharge and stress on slopes by weight of vegetation as explained in Equation 2.3 (Selby, 1993), as well as reinforcement of soils by plant roots (Table 2.3):

$$Effect\ of\ surcharge, \frac{T\cos\beta\tan\phi'}{T\sin\beta} \qquad \textit{Eq. 2.3}$$

where T = weight of tree (kPa)

β = slope angle (º) and

ϕ' = friction angle (º).

Shear stress can be enhanced on a slope by $T\sin\beta$ while normal stress in increased $T\cos\beta$. On slopes less than 34º, trees increase stability, but when slopes are greater than this angle, effect of tress may be disadvantageous to slope stability (Selby, 1993).

Table 2.2: Effects of vegetation on slope stability (Greenway, 1987). A – Adverse, B – Beneficial.

Hydrological mechanisms	**Influence**
Interception of precipitation and initiation of evaporation thus reducing available moisture for infiltration	B
Increased roughness of ground surface by roots and stems thus increasing permeability and infiltration capacity	A
Extraction of soil moisture by roots and subsequent transpiration thus reducing pore-water pressure	B
Depletion of soil moisture may accentuate desiccation cracking in the soil resulting in higher infiltration capacity	A
Mechanical mechanisms	
Reinforcement of soils by roots and subsequent increase in shear strength of slope materials	B
Provision of support to upslope soil mantle by tree roots	B
Weight of trees may increase surcharge on slopes, increasing normal and downhill force components	A/B
Transmission of dynamic forces into slopes by vegetation	A
Roots bind soil particles at the ground surface, reducing their susceptibility to erosion	B

Table 2.3: Strength added to soil by plant roots (Selby, 1993)

Plant	Soil	Increase in apparent cohesion (kPa)
Conifers (pine, fir)	Glacial till	0.9 – 4.4
Alder	Silt loam	2.0 – 12.0
Birch	Silt loam	1.5 – 9.0
Podocarps	Silty gravel	6.0 – 12.0
Barley	Silty-clay loam	1.0 – 2.5
Clover	Silty-clay loam	0.1 – 2.0

Increase in logging activities increases frequency and occurrence of landslides (O'Loughlin, 1972; Rood, 1984; Guthrie, 2002) which could be attributed to two reasons: First, deforestation exposes the soil to direct impacts of raindrops and surface runoff which can encourage gully incision. When the walls of the gully channels attain steep slope angles, landsliding can occur. Secondly, dead roots can create local channels for infiltration and this situation can contribute to infiltration-induced pore pressure which encourages landsliding (Collison & Anderson 1996). However, it is also possible that deforestation might increase runoff thereby decreasing infiltration and pore water pressure, thus reducing landslide occurrence (Blong and Dunkerley 1976).

Land-use changes caused by increased demographic pressure influence gully erosion (Fanciullacci, 1978; Hishe et al. 2020). Four stages of development (Figure 2.2) can be inferred from the influence of higher demographic pressure on gully erosion. First, increase in population density. Secondly, high population density led to economic and other demographic pressures on the environment, removal of natural vegetation as well as reduction of bush fallow period from 15-20 years to as little as one year (Fanciullacci, 1978). Removal of vegetation cover exposed soils to direct impacts of rainfall and surface runoff, while reduction of fallow period reduced recovery ability of soils. Thirdly, in addition to the already shortened fallow period, extensive land-use changes over the years; natural forests were cleared for plantation agriculture and farmlands, subsequently, farms were cleared for hard engineering constructions, thus, within a short period of time, former forests were converted into paved and impermeable surfaces.

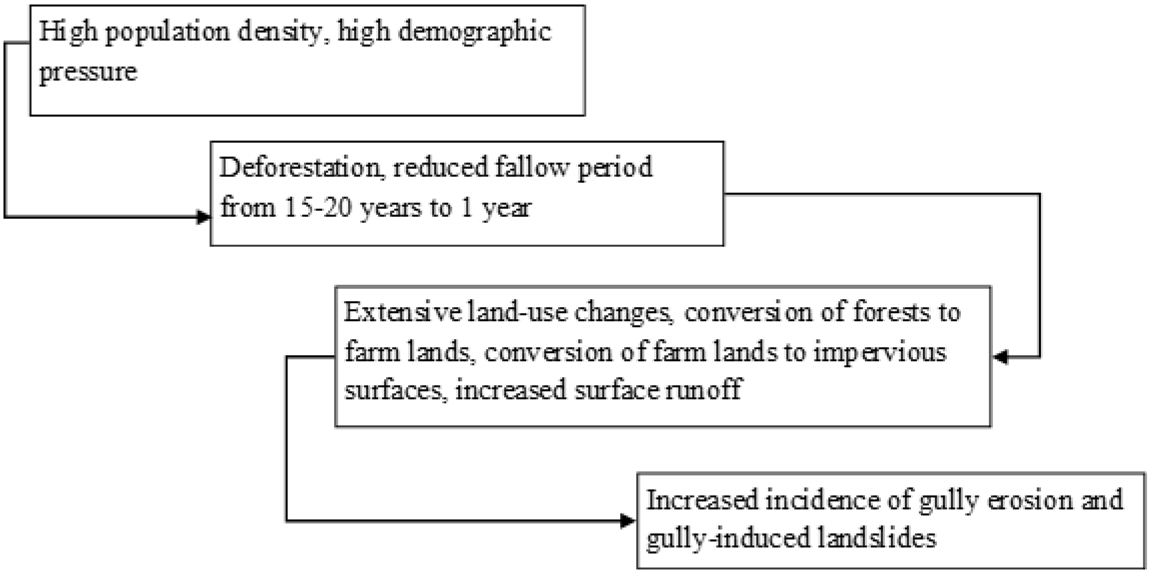


Figure 2.2: Demographic pressure as a factor of gully erosion, proposed by Fanciullacci (1978)

Finally, paved surfaces led to an increase in volume of storm water and runoff (Njoku et al. 2017) and likely increase in the incidence of gully erosion and gully-induced landslides (Attah et al. 2013). Apart from the four stages of relationship between higher population and gully erosion identified above, increase in population also forces people to cultivate marginally stable lands thus facilitating gully erosion (Hagos et al. 1999; Hishe et al. 2020). Growing population density increases the problems associated with landsliding (Knapen et al. 2006). Land-use changes can:

1. Reactivate old landslides by removal of toe support,
2. Initiate new landslides especially, if such slopes are marginally stable,
3. Result in an increase in the frequency of occurrence of landslides due to slope-support undercutting by human activities (Guthrie 2002).

Excavation of borrow pits and sand mining cause gully erosion and landsliding (Igbokwe et al. 2008; Nwachukwu & Eburukevwe, 2013). In search of laterite for engineering construction, contractors embark on borrow pit excavation, soon after excavation, these pits are left derelict. Irregular surfaces and steep slope angles created during sand mining may create favourable conditions for concentration of surface runoff, initiation of gully erosion and subsequent increase in susceptibility of pit sites to sliding.

2.2.5 Nearness to roads and rivers

Roads are an example of both land use and change in land use. Road construction, especially, asphalt roads, involves removal of vegetal cover (if any) and conversion to an impermeable paved surface which induces a concentration and a diversion of concentrated runoff which enhances gullying (Nyssen et al. 2002). Apart from asphalt roads, farm roads and footpaths can also lead to concentration of runoff thereby initiating new gullies or expanding existing ones (Frankl et al. 2019; Yibeltal et al. 2019a). Distance from roads has an inverse relationship with susceptibility to gully erosion (Rahmati et al. 2017; Zabihi et al. 2018) which can be linked directly to the environmentally unfriendly behaviours of some road contractors who do not channel storm water generated from road runoff appropriately. Due to the kinetic energy of road runoff, improper termination of road runoff by careless attitudes of road contractors can increase susceptibility to erosion (Nwankwor et al. 2015). Improper termination refers to the condition whereby drainage channels designed to collect storm water away from roads are not terminated at local base levels. This condition gives room for gradual but steady erosion of drainage channels and subsequent initiation of gully.

Idowu & Oluwatosin (2008) suggested that soils of south-eastern Nigeria have high erodibility potential and are classed as structurally unstable, thus making them susceptible to gully erosion. This notion of structural erodibility was however opposed by Nwankwor et al. (2015) who noted that soils in this region were not easily erodible as is hitherto believed. Nwankwor et al. (2015) concluded that most gullies in south-eastern Nigeria can be traced back to improper termination and unplanned diversions of road runoff concentration. While studies from different parts of the world for example, southern Spain (Collison, 2001), northern Ethiopia (Frankl et al. 2012), the Ilam Province of Iran (Rahmati et al. 2017) agree there is higher concentration of gullies nearer the roads, there is paucity of reported studies on the relationship between nearness to roads and changes in gully sizes. Apart from road construction, other engineering projects, when not effectively managed, can enhance gullying. For example, formation of gullies in the arid mountainous Andean environment was related to the spill over of irrigation water or collapse of open irrigation canals and reservoirs (Vanacker, et al. 2003). This collapse supplied large amounts of water to structurally poor soils, which caused further incision and extension of existing rill and gully network (Vanacker, et al. 2003).

In a study of 109 gullies in the Mazandaran Province of Iran, Zabihi et al. (2018) observed a higher concentration (63%) of gullies within 50 m of rivers. Rahmati et al (2016) observed that distance from rivers was an important driver of gully erosion, their study found that as distance from rivers increased, occurrence of gullies declined. Other studies (e.g. Conoscenti et al. 2014) have identified higher concentration of gullies near rivers, while observing that land use changes also influence gullying. However, the interaction between nearness to rivers and land use changes and likely effects of this interaction on changes in gully sizes are not clear.

2.2.6 Soil characteristics

Influence of soil characteristics such as shear strength, cohesion, degree of weathering, drainage potential, infiltration rate, particle size content, as well as thickness on gully erosion and landsliding have been studied (Okagbue & Ezechi, 1988; Larsson 1989). The high sand content (90% sand content in places), low cohesion (15 kN/m^2 at some sites) and high infiltration values of soils (up to 3571 mm/h) in southeast Nigeria make the soils susceptible to dispersion by erosive forces and seepage erosion (Okagbue & Ezechi, 1988). Due to the loose, coarse, and pebbly nature of the sands in this region, there is high internal flow rate of sub-surface flow (Egboka et al. 1985). Where there is interbedding of permeable sandy soils and less permeable clay soils, variation in infiltration could lead to the formation of a perched water table at the interface between sand and clay, and thereby facilitating slope instability (Akpan et al. 2015).

Decrease in the shear strength of the soil reduces resistance to landsliding and certain factors including increase in the degree of weathering (Veder 1981) and increase in water absorption and resulting swelling (Larsson, 1989) can reduce shear strength of soils. Weathering can increase as well as reduce susceptibility of soil materials to landsliding. On non-ferruginized soils, weathering increases susceptibility to landsliding whereas on ferruginized soils, weathering reduces susceptibility to landsliding (Emeh & Igwe 2017). This reduction in susceptibility is a result of the production of laterites (formed from iron rich sediments under intense weathering) which hardens on exposure to air into nodular concretes or hardpans if layered. These hardpans are highly resistant to erosion and landsliding, on the other hand, slope materials derived from the non-ferruginized (non-lateritic) soils weather into non-plastic fine particles that lack cohesion and are readily dispersed by rainfall (Emeh & Igwe 2017).

Having reviewed relevant literature, I now integrate findings from these studies into a conceptual model of gully-landslide interactions.

2.3 Conceptual model of gully-landslide interactions

Separate conceptual models exist for either gully erosion or landsliding (e.g. Cooke & Reeves, 1976; Ofomata 1987; Egboka & Orajaka, 1987; Gobin et al. 1999; Uzielli et al. 2008). These models were aimed at explaining causative processes, as well as elements at risk of gully erosion and landsliding. However, a model that looks specifically at the interactions between gully erosion and landsliding considering potential significance of ecogeomorphic processes has not yet been developed. Such a model will explain gully-landslide feedbacks and in turn contribute to an improved understanding of earth surface processes in the range of systems where gully-landslide interactions are likely to be important.

The conceptual model developed here is based on reviewed literature and presents the conceptual underpinning of this research into gully-landslide interactions. Climatic, geologic, soil, geomorphic and ecological drivers, have been included in the conceptual model, these identified factors function within an ecogeomorphic system, . The ecogeomorphic system comprises climatic, soil and geologic elements that influence feedbacks between geomorphic and ecological components of an environment. Climatic elements with special reference to temperature and rainfall affect:

1. Ecological responses for example distribution of vegetation (Stephenson, 1990),
2. Initiation and development of geomorphic processes such as landsliding and gully erosion (Obi & Salako, 1995; Zhou et al. 2002; Afegbua et al. 2016),
3. Soil conditions for instance weathering (Brady et al. 1999).

Similarly, ecological drivers, soil characteristics, geologic and geomorphic conditions impact geomorphic processes which in turn influence ecological responses directly by influencing distribution of vegetation (Parker & Bendix, 1996; Stallins, 2006) and local climate indirectly through the effects they have on vegetation, thus forming a continuous loop of interactions within the ecogeomorphic system. Increase in rainfall intensity as well as extreme events such as flooding will likely lead to considerable surface erosion (Obi & Salako, 1995; Ibbitt et al. 1997; Abate et al. 2015; Frankl et al. 2019) and can trigger landslides. Moderate rainfall and temperature will encourage vegetation growth which in turn protects the soils from direct impacts of raindrops and thus reducing soil susceptibility to gully erosion. Prolonged dry periods will enhance gullying (section 2.2.1) .

On the relationship between vegetation and landsliding, section 2.2.4 identified the positive and negative influences of vegetation on landsliding. Human activities such as removal of vegetal cover and increased mining activities are known to increase propensity to gully erosion and gully-induced landslides (Fanciullacci, 1978; Igbokwe et al. 2008; Nwachukwu & Eburukevwe, 2013). Geologic factors can predispose soils to gullying and landsliding (section

2.2.2). Increases in temperature in combination with availability of soil moisture increase the rate, intensity and depth of weathering (Brady et al. 1999). Increased depth of weathering provides sufficient regolith for failure on a hillslope while increased weathering intensity can reduce cohesion and subsequently increase susceptibility of slope materials to failure (Veder, 1981).

Gully erosion can elevate slope angles by gradually removing slope materials until a time when the angle is steep and unstable, thus, increasing shear stress and subsequent propensity to landsliding (Igwe & Fukuoka, 2010) (figure 2.3A). Equally, slope toe support can be eroded by gully erosion, thus, activating/reactivating sliding (Igwe. et al. 2014; Maduka et al. 2017) (figure 2.3B). On slopes that have no history of landsliding, removal of toe support can increase exposure and vulnerability to sliding, on old landslide complexes, removal of toe support can reactivate landslides. Landslides can enhance erodibility of soils by creating bare surfaces that are attacked by surface runoff, creation of depressions and uneven surface geometries with abrupt changes of steepness in the land and favouring concentration of surface runoff (Johnson & Warburton, 2015; Gómez-Gutiérrez et al. 2015). Gully erosion begins when runoff concentrates into these depressions and channels thus leading to:

1. Incision or
2. The development of rills which may later enlarge into deep trenches in the land surface over time (Luffman et al. 2015), or a combination of both processes.

The dashed lines in figure 2.4 show linkages between gully erosion and landsliding as explained in Table 2.4. Landsliding can reduce vegetal cover and expose soils to agents of erosion. Similarly, landslide scars create uneven geometries and magnify surface runoff on the steepest points of these uneven surfaces thus enhancing erodibility of materials and increasing susceptibility to gully erosion. Finally, gully erosion undermines slope stability in three ways; by removing toe support; by steepening slope angle and by exposing shear surfaces thereby increasing instability in the slope.

Table 2.4: Interactions between gully erosion and landsliding

Gully erosion	**Landsliding**
Increases slope angle to unstable angles thus increasing susceptibility to landsliding	Enhances erodibility of slope materials by removing vegetation cover Removal of vegetal cover reduces resistance to surface flow
Removes toe support by gully and slope undercutting thereby increasing susceptibility to landsliding	Landslide scars create depressions and uneven geometry
Can expose shear surface between permeable and non-permeable materials on a hill slope	Surface runoff erosivity is magnified at steepest points in depressions created by landslide scars and this encourages gully incision by surface runoff

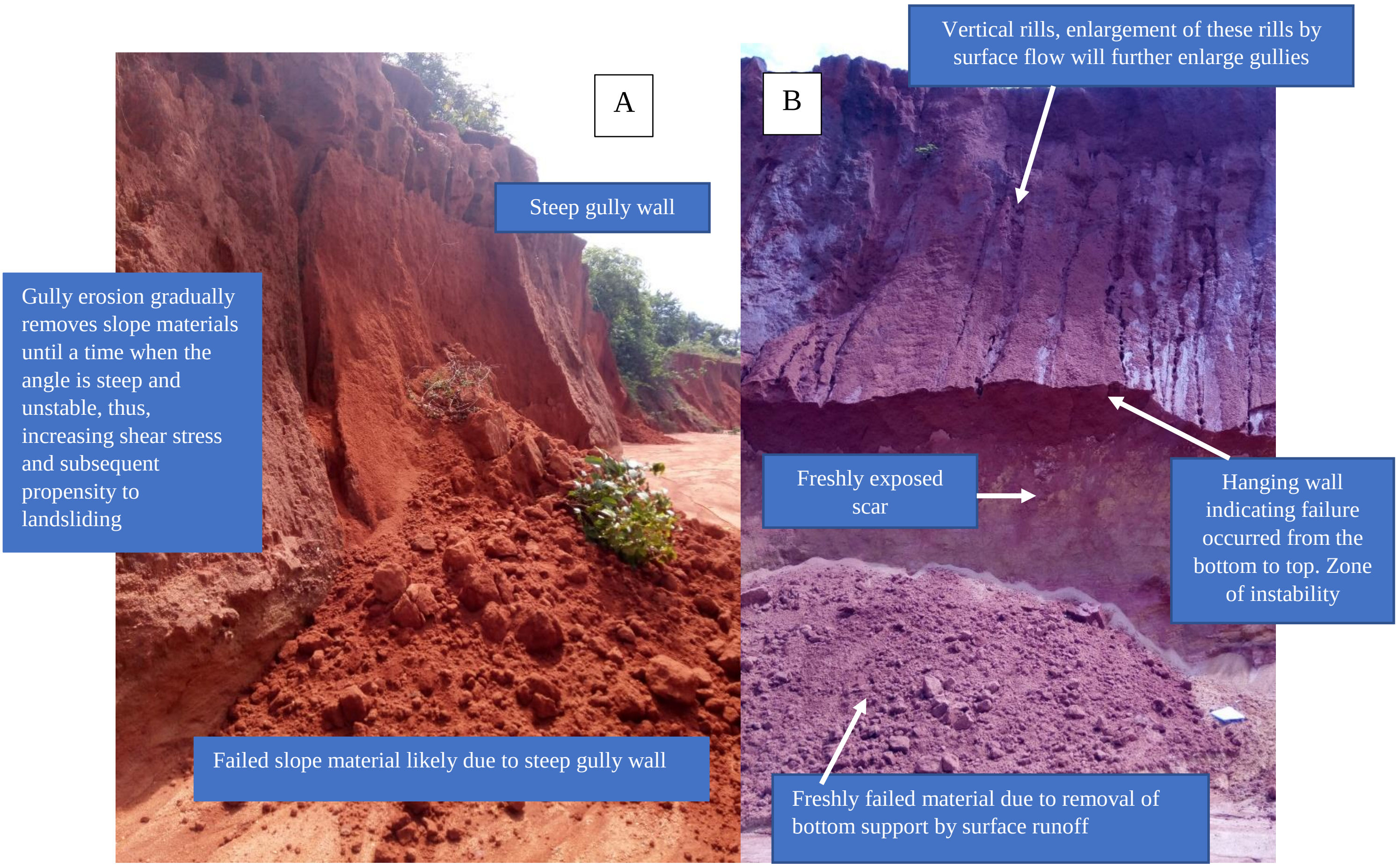


Figure 2.3: Gully-induced landslides. A, Block failure in Obibi-Ochasi gully. Gully erosion leads to steep slope angles, thus enhancing block failure, B, Soil fall in Obibi-Ochasi likely caused by removal of toe support.

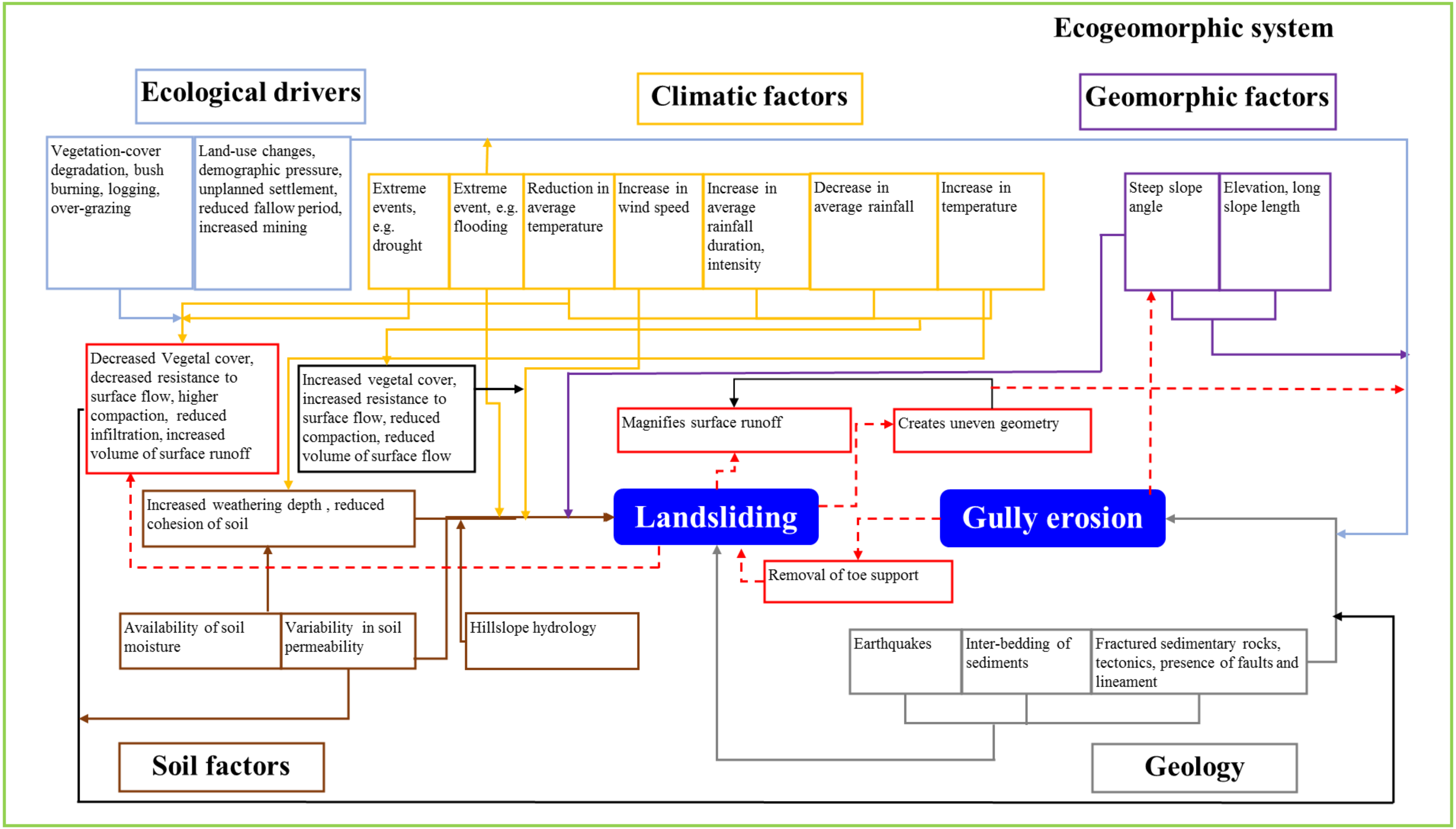


Figure 2.4: Ecogeomorphology of gully-landslide interactions. Red boxes and dashed lines show feedbacks between gully erosion and landsliding, green box indicates the ecogeomorphic system as explained in text. Individual drivers whose interactions with one another initiate gullying or landsliding are coloured with different colours.

2.3.1 Established gaps and research questions

The above reviewed literature has demonstrated mechanisms of gully erosion and landsliding, while identifying driving factors. Identified studies have looked at single-process domains (e.g. either landsliding or gully erosion) however the present study aims to understand both processes together so as to answer questions such as how have interactions among driving factors affected gully-landslide interactions? There is a dearth of knowledge on the:

1. Interactions among the identified gully-driving factors and changes in gully sizes and,
2. Interactions among gully-driving factors and gully-landslide interactions.

Attempts to fill the first part of the identified gap (interactions among gully-drivers and changes in gully sizes) were undertaken by Conoscenti et al. (2014) and Iro (2018). Both studies adopted analysis of remotely sensed data and quantitative techniques (logistic regression and multiple regression analyses) to achieve their objectives. While the former study produced a susceptibility map of gully erosion as an end product, they did not explore the interactions among gully-drivers and changes in gully sizes. Iro (2018) did not include nearness to roads and rivers in his analysis, both factors are significant in gully evolution (evidenced from literature review). Furthermore, while the study by Iro (2018) identified the individual roles of gully drivers such as slope gradient, elevation, curvature and change in land use in controlling gully distribution, it was not clear how combined effects of these factors influenced changes in gully sizes (e.g. length and area). Whilst previous researchers have observed that gully erosion leads to landsliding (Igwe. et al. 2014; Maduka et al. 2017), there is no known documented study on the linkages between gully/landslide driving factors and gully-landslide interactions.

2.3.2 Research objectives

The following are the objectives of this research:

1) To establish the influence of land use and land-use changes on gully characteristics.
2) To ascertain the effects of land-use changes on gully catchment hydrology. Fulfilling objectives 1 and 2 will improve understanding of processes driving gully erosion.
3) To understand the influence of land-use changes on gully-landslide interactions. This objective will aid the design of appropriate control measures.
4) To determine resultant hazards and effects of gully-landslide interactions on affected communities. Achieving this objective will inform interested parties of the challenges gully-endemic communities face and aid possible compensation strategies on the side of the government.

To provide answers to these identified gaps and fulfill the research objectives, in the next chapter a multi-method approach including geotechnical investigations, qualitative research, quantitative techniques, analysis of remotely sensed data and hydrological modelling is used to study gully-landslide interactions. Few studies have incorporated quantitative and qualitative research techniques (Nyssen et al. 2006; Tebebu et al. 2010; Frankl et al. 2016) while this is the first time to the best of my knowledge these research approaches are used together in a study of this kind in southeast Nigeria. This work is novel because of three reasons: First, combinations of these research techniques in a single study. Secondly, working across process domains (gully erosion and landsliding) and finally, taking an ecogeomorphic perspective to provide a more holistic overview.

Chapter 3

Materials and methods

3.0 Introduction

This chapter describes the study area and sites. It also provides detailed information about methods used in this study. Chapter 3 is divided into two main sections; the first section defines the study area and sites while the second details methods adopted to achieve set objectives. Multi-method research techniques have been used in data-scarce regions in order to improve understanding of geomorphic processes (Frankl et al. 2016). Due to insufficient data in the study area, combinations of analysis of remotely sensed data, qualitative and quantitative techniques, geotechnical investigations, and hydrological modelling were adopted in this work. Details of these techniques are provided in section 3.2.

3.1 Study area and study sites

In Nigeria, gully erosion and gully-induced landsliding are most pronounced in the south east (Figure 3.1), located within latitudes 4° 47' 35" N and 7° 7' 44" N, and longitudes 7° 54' 26" E and 8° 27' 10" E, (Okorafor et al. 2017), where population densities rank among the highest in rural Africa (Eboh et al. 1994; Onu, 2006; Okorafor et al. 2017). Population density estimates are up to 6030 people per square kilometre in some parts of southeast Nigeria (Table 3.1). These high population densities, coupled with high demographic pressures are often implicated as possible drivers of gully erosion and gully-induced landslides (Fanciullacci, 1978; Ofomata, 1987). Farming is the primary employer of labour in rural areas; major food crops include cassava (*Manihot esculenta*), yam (*Dioscorea*) and maize (*Zea mays*) while oil palm (*Elaeis guineensis*) is a common cash crop. Subsistence farming is popular in the study area. The farming season begins with bush burning just before the outset of rainy season towards the end of March. Bush burning leaves the soils without vegetation cover as the rains start in earnest and thereby increasing susceptibility to erosion (Igwe et al. 2014). Cassava is the dominant food crop; however mixed farming is also practised. It is common to find a piece of land with cassava and maize inter-planted.

3.1.1 Geology, soils and rivers

South east Nigeria lies within the Lower Benue Trough characterised by gently undulating topography (Benkhelil, 1989), the Benue Trough is divided into three: The Upper, Middle and Lower Troughs. The Lower Benue Trough includes the Abakiliki Anticlinorium and the Anambra Basin. The Abakiliki Anticlinorium is thought to have been formed of tightly folded

Cretaceous sediments intruded by numerous magmatic rocks and extends from the Niger Delta to the Gboko-Ogoja area in a N50º E direction covering a distance of about 250 km (Benkhelil, 1989). The Anambra basin is a synclinorial structure trending in a N30º E direction and comprises a thick undeformed Cretaceous series (Benkhelil, 1989).

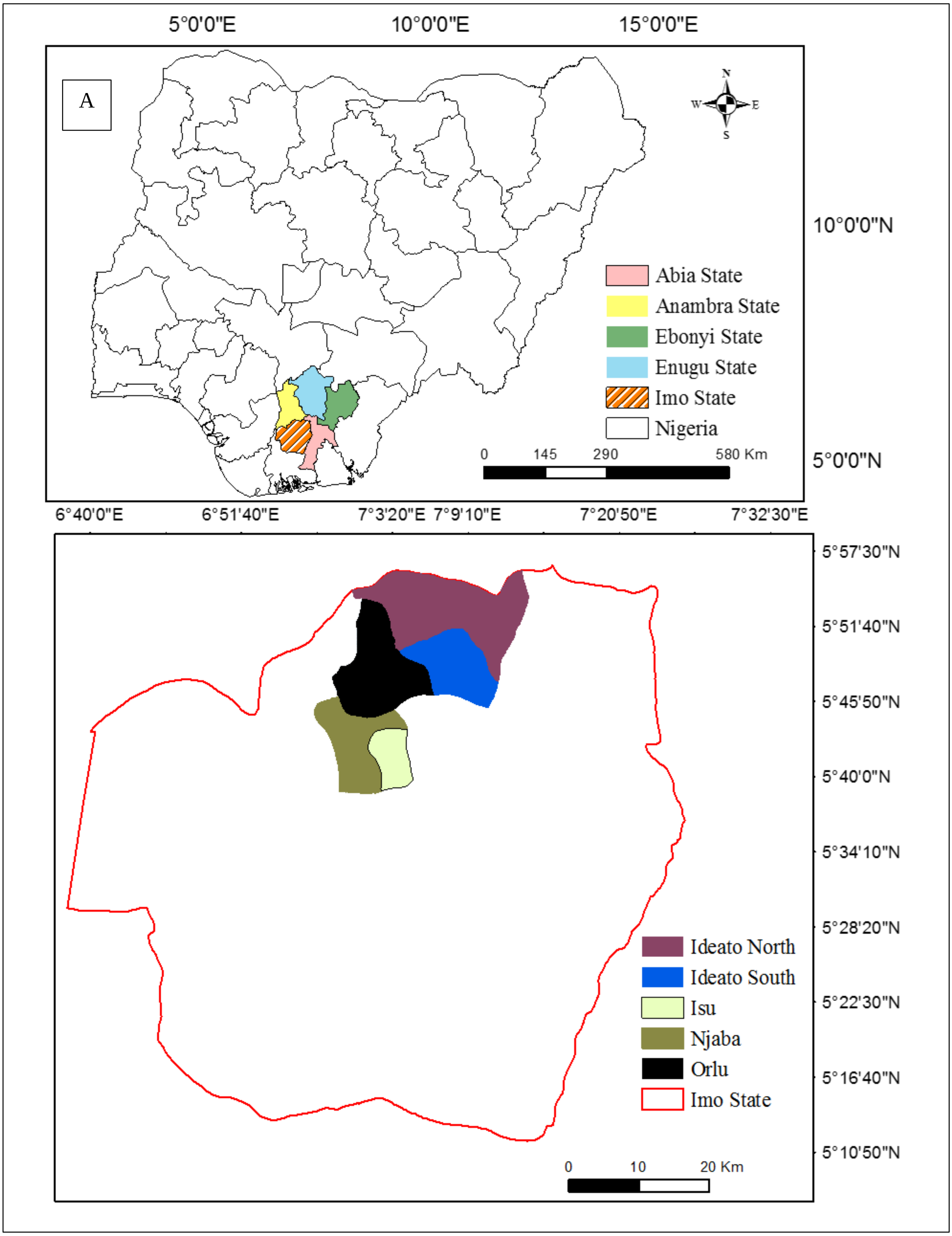


Figure 3.1: *A, Nigeria showing five south east States, Abia, Anambra, Ebonyi, Enugu, Imo, B, Imo State showing 5 Local Government Areas (LGAs) of interest. Imo State is one of the southeast states.*

The general stratigraphy of south east Nigeria is presented in Table 3.2. Four geological formations underlay the study sites in Imo State: Imo Shale, Benin, Ogwashi-Asaba and Ameki Formations (Usman et al. 2014) (figure 3.2).

Table 3.1: Local Government Areas under investigation showing landmass and high population density. 2018 Population was estimated from the 2006 official census figures and projected to 2018 with an annual growth rate of 3.25 %.

LGA	2018 estimate of population density (people per km^2)	Land area (km^2)
Ideato North	1207	190
Ideato South	2663	88
Isu	6030	40
Njaba	2507	84
Orlu	1588	132

Table 3.2: Stratigraphy of Southeast Nigeria, (Source: Maduka, et al. 2017).

Age	Stratigraphic unit
Eocene	Ameki Group (including Nanka Sands, Nsugbe Formation)
Palaeocene	Imo Shale
Maestrichtian	Nsukka Formation, Ajali Sandstone, Mamu Formation
Campanian	Nkporo Group (including Nkporo Shale, Oweli Sandstone, Enugu Shale, Afikpo Sandstone, Otobi Sandstone)
Santonian	Non-deposition
Coniacian	Awgu Group (including Awgu Shale, Agbani Sandstone)
Turonian	Ezeaku Formation (including Amaseri Sandstone)
Cenomanian	Odukpani Formation
Albian	Asu River Group
Precambrian	Basement Complex

The Imo Shale is dated Palaeocene to lower Eocene and is estimated to be ca. 1000 m thick, it contains three sand bodies – Ebenebe Sandstone, Umuna Sandstone and Igbaku Sandstone (Ekwenye et al. 2014). The Benin formation (Miocene – recent) contains sand beds with minor clays, lignite, and conglomerate intercalations (Amajor, 1991). The Ogwashi-Asaba Formation of Oligocene – Miocene age consists of a sequence of coarse-grained sandstone, light coloured clay and carbonaceous shale with lignite intercalations (Ogala et al. 2012). The Ameki Formation is considered to be either early Eocene or early middle Eocene. It is lithologically heterogeneous and has been divided into four lithological units which are, in ascending order: silty to calcareous sandstone, grey to dark shale with interbedded siltstone, silty to fine argillaceous sandstone and fine to coarse pebbly sandstone (Sonibare et al. 2012). Two major rivers, Njaba and Orashi have their sources within the study sites (figure 3.2). While the Njaba rises from four communities; Amucha, Eziama, Isu Njaba and Ekwe, the Orashi has its source from the Isiekenesi Waterfalls. Other streams such as Okpii and Ezizi (tributaries of Orashi) also have their source located within the study sites.

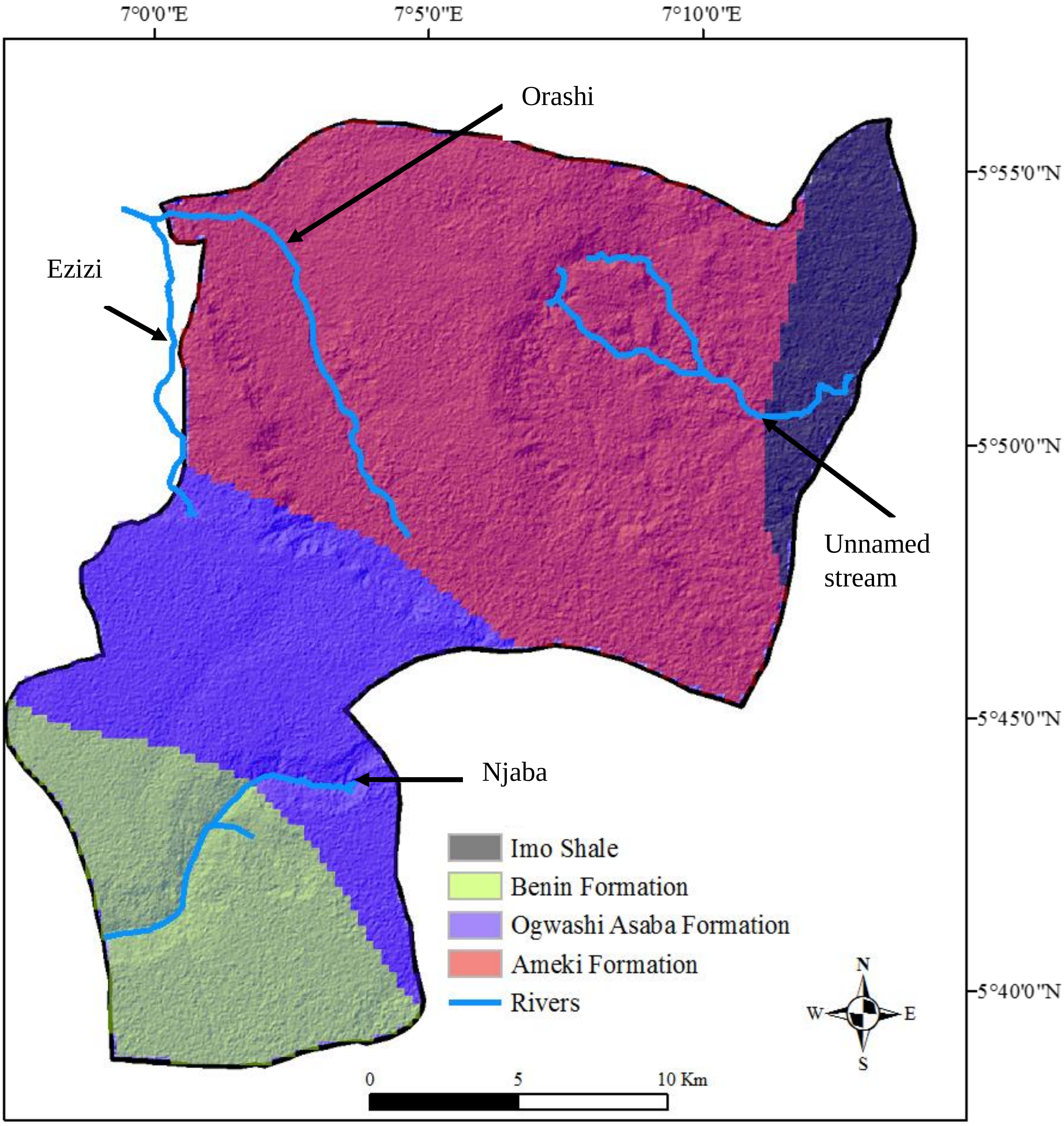


Figure 3.2: Geology and river map of LGAs of interest draped on shaded relief map. The Njaba and Orashi are the two major rivers in the area, other streams such as Ezizi and an unnamed stream also take their courses from the study area.

Prominent geomorphic features in the landscape of south east Nigeria include the Awka-Orlu uplands and Enugu-Awgu-Okigwe escarpment (Egboka et al. 1990; Obi et al. 2001). Soils in south east Nigeria are heterogeneous in nature comprising of loose red earth with sands, sandstones and clayey-loam with or without ferric properties underlain by shale formations, they are acidic with low organic content as a result of leaching from surface runoff (Okoroafor et al. 2017). The soils have higher sand contents with low silt/clay composition which decreases with depth making the sands cohesionless, very permeable with high infiltration rates of up to 3571 mm/hr (Obi & Asiegbu, 1980; Chiemelu et al. 2013; Okorafor et al. 2017).

3.1.2 Climate and vegetation

The study area has a tropical climate with humidity and rainfall decreasing from the coast inland. South east Nigeria is characterised by uniformly high temperature and a seasonal distribution of bimodal rainfall (Monanu, 1975: Ezemonye & Emeribe, 2012). Mean minimum and maximum temperatures range from 21-30°C in the coast and 29-33°C in the interior, rainfall generally is intense and ranges from over 2500 mm annually in the southernmost region towards the Atlantic to about 1500 mm around River Benue in the northern borders (Chukwu, 2007; Ezemonye & Emeribe, 2012; Igwe, 2012). There is a long wet season from April to July with a short, dry season (August break) followed by a short wet season (September to October) and finally by a long, dry season (November to March) (Obi & Salako, 1995).

Rainfall intensities in the range of 100 to 125 mm h^{-1} are likely to occur more than five times a year in south east Nigeria, intensities between 125 and 150 mm h^{-1} are not uncommon, whereas those greater than 150 mm h^{-1} are rare (Obi & Salako, 1995). Rainfall erosivity indices range from very low to very high with periods of very low erosivity coinciding with the dry season months while very high erosivity periods correspond with the rainy season peak periods (June-September) (Ezemonye & Emeribe, 2012). Figures 3.3A shows 2016 rainfall distribution for Nigeria and 3.3B shows average monthly rainfall and rain days for one of the Local Government Areas (LGAs) of interest between 2009 and 2018.

South east Nigeria lies within the rainforest vegetation belt with evergreen trees (Ezemonye & Emeribe, 2012). Due to demographic pressures, this natural rainforest has been disturbed over the years, a situation which has resulted in derived forests in place of natural forests.

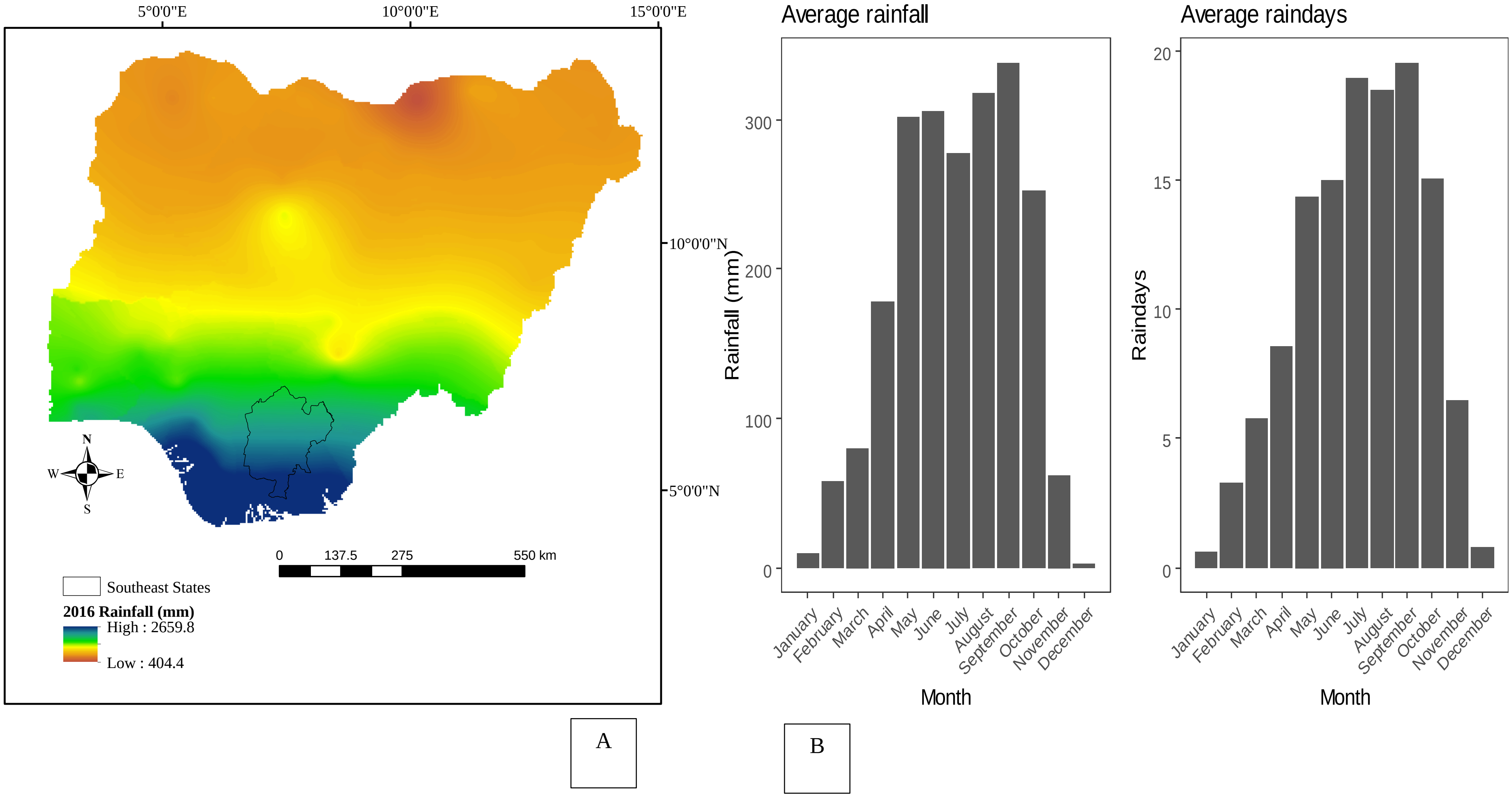


Figure 3.3: A, 2016 Rainfall distribution in Nigeria showing reduction in rainfall from south to North, B, Average rainfall and rain days between 2009 and 2018 for Ideato North LGA. August and September are the wettest months of the year while July and September have the highest rain days. Source (Nigeria Meteorological Agency, NIMET, rainfall data for Ideato North, 2009 to 2018).

3.1.3 Study sites

Imo State (Figure 3.1B) is one of the southeast states where gully erosion is endemic. Administratively, the State comprises three senatorial zones: Okigwe, Orlu and Owerri, each zone is made up of a number of Local Government Areas (LGAs). The Orlu senatorial zone of Imo State with an area of 2,293 km^2 was selected for detailed study of gully-landslide interactions, this selection is because the Orlu zone has the highest concentration of gully erosion in Imo State (Okorafor et al. 2017).

There are 12 Local Government Areas (LGAs) in Orlu Zone: Ideato South, Ideato North, Isu, Njaba, Nwangele, Ohaji-Egbema, Oguta, Orlu, Oru West, Oru East, and Orsu. Severe gully erosion and gully-induced landsliding in Orlu Senatorial Zone has been documented in Ideato North, Ideato South, Isu, Njaba and Orlu Local Government Areas (Osuji, 1984; Iheme et al. 2016) and these LGAs with an area of 534 km^2 were studied in this research. Fieldwork was conducted between April and June 2019; these months were specifically selected for two reasons: April falls within the start of rainy and thus to reduce delays caused by intense rainfall in the middle of the rainy season. Secondly, both gully erosion and landsliding are affected by rainfall, therefore, fieldwork was planned to coincide with a period when the effect of rainfall will be visible on gully slopes but not intense to significantly disrupt field visit.

3.2 Methods

In this section, methods used to achieve research objectives are explained.

3.2.1 Objective 1: Influence of land use and land-use changes on gully characteristics

To achieve objective 1, the following research questions were posed:

I. Have there been land-use changes in the study area between 2009 and 2018? High resolution data covering the entire study area were available for 2009 and 2018, hence the start date of 2009.
II. Have gully characteristics changed between 2009 and 2018?
III. What other factors interact with land-use changes to influence changes in gully characteristics?

3.2.1.1 Land-use classification

To answer the question regarding influence of land use and land-use changes on gully characteristics, the land uses in the study area had to be classified and it had to be established that land-use changes have indeed occurred in the study sites between 2009 and 2018. RapidEye Satellite imagery covering the area were available for 2009 and 2018 (Table 3.3) and were used for classifying land use. WorldView2 data captured in 2014 covered some parts of the study area and were used for land-use classification in these areas.

Table 3.3: Satellite imagery used for 2009 and 2018 land use classifications.

Satellite	Source	No. of bands	Spatial resolution (m)	Cloud cover (%)	Date of acquisition
RapidEye -1	Planet.com	5	5	0	November, 2009
RapidEye-3	Planet.com	5	5	0	December, 2018

Supervised classification using the false colour composites of near infrared, red and green bands, were used for land-use classification. This colour composite scheme was used to identify the signature of different land-use classes (Hishe et al. 2020) and thereby improve land-use classification. In this false colour composite, vegetation appeared in different shades of red depending on their type and conditions (for example, tree canopies had very bright red colours) while bare surfaces appeared in various shades of blue or grey. Three types of land use classes were identified; non-vegetated, open vegetation and fallow/trees. Non-vegetated refers to bare surfaces, built environments, gullies and borrow pit sites. Open vegetation refers to grasses and farms while trees denote areas under tree-cover and fallow. The LGAs of interest are predominantly rural (except the Orlu Township), and land is used either for building or farming or is left to fallow, hence, the three land use classes adopted in this study. In line with standard practice, and to determine the accuracy of thematic land use maps, accuracy assessments were carried out for the maps. 90 validations points were generated on the RapidEye high-resolution satellite imagery, each validation point was assigned to a corresponding land use based on physical interpretation of the imagery. These validation points were tested on the land use maps produced for accuracy and agreement. A stratified confusion matrix was computed to compare true classes with mapped classes and summary statistics such as overall, producer and user accuracies as well as kappa statistics were computed (Appiah et al. 2018) as shown in Equations 3.1 – 3.4.

$$Overall\ accuracy\ (\%) = \frac{Number\ of\ correctly\ classified\ class}{Total\ number\ of\ reference\ points} * 100 \qquad \textit{Eq. 3.1}$$

$$Producer\ accuracy\ (\%) = \frac{Number\ of\ reference\ sites\ classified\ accurately}{Total\ number\ of\ reference\ points} * 100 \qquad \textit{Eq. 3.2}$$

$$User\ accuracy\ (\%) = \frac{Total\ number\ of\ correct\ classifications\ for\ a\ paricular\ class}{Row\ total} * 100 \quad Eq.\ 3.3$$

$$k = \frac{N \sum_{i=1}^{n} mi,i - \sum_{i=1}^{n} (G_i\ C_i)}{N^2 - \sum_{i=1}^{n} (G_i\ C_i)} \quad Eq.\ 3.4$$

where:

k is Kappa statistics

i is the class number

N is the total number of classified values compared to truth values

$m_{i,i}$ is the number of values belonging to the truth class i that have also been classified as class i (i.e., values found along the diagonal of the confusion matrix)

C_i is the total number of predicted values belonging to class i

G_i is the total number of truth values belonging to class i

The overall accuracy is the total number of correctly classified samples (diagonal cells of the matrix) divided by the total number of samples and measures the accuracy of the entire image without any indication of the accuracy of individual categories (Fung and LeDrew 1988). The producer’s accuracy is the number of correctly classified samples of a particular category divided by the total number of reference samples for that category. It is a measure of the error of omission (Story and Congalton, 1986; Fung and LeDrew 1988). The user's accuracy is an alternative measure for individual category accuracy, and it is the number of correctly classified samples of a particular category divided by the total number of samples being classified as that category. It measures the error of commission (Fung and LeDrew 1988). The kappa coefficient of agreement (k) was developed by Cohen (1960) and is a measure of the actual agreement (indicated by the diagonal elements of the matrix) minus chance agreement (indicated by the product of row and column marginals). The kappa coefficient uses all cells in the matrix and takes into account both the commission and omission errors (Rosenfield and Fitzpatrick-Lins, 1986; Fung and LeDrew 1988).

3.2.1.2 Changes in gully characteristics between 2009 and 2018

To identify changes in gully characteristics between 2009 and 2018 (research question 2, section 3.2.1), gully mapping and geomorphological fieldwork were conducted. Gully mapping was undertaken using satellite imagery (Table 3.4). Geomorphological fieldwork was used to ground-truth mapped gullies. Also, a drone survey was carried out during fieldwork by Loraj Consortium (one of the consultants working on the Nigeria Erosion and Watershed Management Project, NEWMAP) and finished products (such as orthophoto) from this exercise were obtained and used to update the gully map.

Table 3.4: Satellite imagery used for gully mapping. Apart from the RapidEye data, other satellite data do not over the entire study sites, hence, while they were appropriate for gully mapping, they were not suitable for land use classification.

Satellite	Source	No. of bands	Spatial resolution (m)	Cloud cover (%)	Date of acquisition
RapidEye -1	Planet.com	5	5	0	November, 2009
RapidEye-3	Planet.com	5	5	0	December, 2018
QuickBird-2	DigitalGlobe foundation	4	(0.61 m and 2.4 m)	0.16	December, 2006
QuickBird-2	DigitalGlobe foundation	4	(0.61 m and 2.4 m)	0.16	December, 2007
WorldView-2	DigitalGlobe foundation	8	2	0	January, 2014
WorldView-2	DigitalGlobe foundation	8	2	0	December, 2017

Gully mapping was carried out by digitizing gullies that were observable in the satellite imagery, using a UTM 32N projection. Gully attributes (identification numbers, area, length and width) were stored in the attribute table. Sand mining from borrow pits/sand pits is an economic activity in the study area. In classifying gullies, separating borrow pits from gullies could be challenging due to the difficulty of knowing the exact demarcation of pits and onset of gully erosion as a result of sand excavation; sand mining increases susceptibility to gully erosion and gully-induced landslides (Igbokwe et al. 2008; Nwachukwu & Eburukevwe, 2013). Hence, researchers often include borrow pits in their gully inventories thereby inflating the number of identified gullies from satellite imagery (Amanbagara, et al. 2015). Based on this observation steps were adopted to avoid classifying borrow pits as gullies. For example, identified gullies were elongated narrow features running for several meters in length, whereas sand mining pits were round features covering several meters in diameter and thus, a separate polygon was used to map borrow pits.

In order to understand changes in gully characteristics and relate same to changes in land use, gully dimensions (length, width and area) were computed after mapping. The longest part of the gully, from start to finish was recorded as length (km). To measure gully widths (m), lateral measurements perpendicular to a centre line were taken at 1 m intervals and an average derived. This derived average is referred to as average gully width. The area of the polygon represented gullied area (m^2).

The primary focus of fieldwork was to ground-truth gullies mapped during desk study. A hand-held GPS (Garmin Oregon 300 model) was used to take gully coordinate points in five visited communities, Amucha, Obibi-Ochasi, Isu Njaba, Urualla and Umueshi. These points were imported into the geoprocessing software (ArcGIS) used for gully mapping and this step was adopted so as to know if coordinates points collected in the field matched the already mapped gully polygons in those communities. Hydrogeology of gullies (discharge of ground water at gully slopes, return flow, presence of springs), gully properties (length, width) and identification of land-use types and cultivation practices were observed and recorded. To measure gully length of visited gullies, coordinate points were acquired at the start and end points of the gully, these points were imported into the geoprocessing software and the distance function was used to measure the length. The same procedure was used to measure gully width.

As part of their monitoring programme, the Loraj Consortium conducted a drone survey of the Urualla area in Ideato North LGA using a DJI Phantom 4 drone flying at an altitude of 242 m on 7th May 2019. 1399 images covering an area of 15.8 km^2 were captured, 21 Ground Control Points (GCP) were acquired using a Trimble R8 AND R7 dGPS and image processing was achieved using Agisoft PhotoScan professional (version 1.4.1 build 5925). Finished products included orthomosaic, DEM (0.4 m resolution) and PointCloud data. The orthophoto was used to update the gully map for the identified gullies. Due to logistical challenges, more drone surveys could not be conducted in the study area before the end of the fieldwork.

To determine changes in gully characteristics, the 2009 values (i.e. length, width and area) were subtracted from 2018, and the difference represented change in gully characteristics.

3.2.1.3 Other drivers of changes in gully characteristics

Two approaches, geomorphic and qualitative (local knowledge of gully-causing factors), were adopted to answer research question 3 (section 3.2.1), what other factors interact with land-use changes to influence changes in gully characteristics? Data on the following factors identified in the conceptual model (figure 2.3) were collected and analysed

a). Geomorphic factors

Previous studies (e.g. Akpan, et al. 2015; Nwankwor et al. 2015; Rahmati et al. 2016, 2017; Zabihi et al. 2018) have identified the importance of other drivers of gully evolution. These factors interact with changes in land use to affect gully erosion and they include geomorphic, climatic and other elements (such as nearness to rivers and roads). These factors are divided into two; physical and human-induced. Physical elements whose interactions with land use affect gully characteristics studied in this work are slope angle, elevation, curvature, proximity to rivers, soil properties, and human-induced factors include change in land use, farming techniques and effects of civil unrest.

Elevation, slope and curvature values were extracted from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 30 m resolution. Different elevation and slope statistics (mean, maximum or range) can be adopted for different purposes depending on the subject of a research. In this study, relative relief (elevation range) and maximum slope values of the gully heads are used to understand changes in gully dimensions. Gullies migrate headwards in response to driving factors, hence the use of these geomorphic variables derived at the gully heads. Relative relief helps the researcher understand the difference between highest and lowest elevation values within a zone of interest, and thus recognize possible routes of surface flow. In a similar vein, use of maximum slope values also helps one understand sites of steepest decent within a zone where the erosive power of surface runoff would be most pronounced. Plan and profile curvatures were classified into three; negative, zero, and positive curvatures corresponding to concave, flat, and convex surface, respectively. Gully counts were identified for the three classes of curvature, and results were used to further understand gullying processes.

Roads and rivers were digitised from the satellite imagery using a line shape file and attributes were stored in an attribute table within the geoprocessing software (ArcGIS). Gully head distance from roads and rivers were calculated while a correlation matrix was produced for relative relief, maximum slope, gully-head distance from road, gully head distance from river and change in gully characteristics. Principal Component Analysis was adopted to understand relative importance of gully-drivers while multiple regression was used to understand the relationship between predictive (gully-drivers) and outcome (change in gully sizes) variables. Gully endpoint distance from roads and rivers were also calculated, these values were not included in the correlation matrix or multiple regression as gullies migrate headwards, and factors that drive this headward expansion were of interest in this study.

Loraj Consortium conducted geotechnical tests (shear strength, cohesion, dry and bulk densities) for four out of the five selected communities representing the study sites: Isu Njaba (Isu LGA), Urualla (Ideato North LGA), Obibi-Ochasi (Orlu LGA) and Umueshi (Ideato South LGA). Soil samples were collected from within the gullies in these communities using a drilling rig at various depths (Table 3.5), while the wet sieving method was used for particle-size analysis. For Njaba LGA, two undisturbed samples were collected from the scarp of a landslide in the Amucha gully (Njaba LGA) for geotechnical test while wet sieving was also used for particle-size analysis. These geotechnical parameters were used to understand response of soils in the area to erosive forces, such as surface runoff. Results from these tests contributed to achieving research aim in the following ways:

1. Strength test results were compared with other published studies to understand potential effects of geotechnical characteristics of soils on gullying,
2. Particle size distribution results informed hydrological soil groups used for hydrological modelling (section 3.2.2) and selection of soil type for infiltration measurements using the minidisk infiltrometer,
3. Particle size distribution results were related to modelling results and field observations to explain likely gully-driving processes.

Table 3.5: Soil samples collected at various depths within gullies; Source: Loraj Consortium, (2019).

LGA	Selected community	Soil test	
		Number of samples	Depth of sampling (m)
Ideato North	Urualla	5	31 – 45
Ideato South	Umueshi	3	0 – 2
Isu	Isu Njaba	4	0.1 – 4.7
Njaba	Amucha	2	Collected at landslide scarp
Orlu	Obibi-Ochasi	5	4 – 6

Apart from the geotechnical parameters of the soils, their infiltration capacities and moisture contents were also studied. Infiltration capacities and moisture contents of soils are important for a better understanding of hydrological drivers of gully expansion in response to land-use changes. Infiltration capacities and particle size analyses informed selection of hydrological groups of soils (section 3.2.2). Infiltration tests were carried out on forested, farmed, and bare soils representing the three land use classifications. The mini-disk infiltrometer was used to undertake infiltration measurements. Hydraulic conductivity, a measure of the rate at which water can move through the soil under certain conditions and hydraulic gradients, is the single most important hydraulic property that affects water flow (Zhang, 1997a and b).

The mini-disk infiltrometer allows measurements of infiltration with a constant negative pressure head at the soil surface and has been extensively used to measure soil hydraulic conductivity (Smetten et al. 1994; Vandervaere et al. 2000; Kargas et al. 2017). The mini-disk infiltrometer is a type of tension infiltrometer that ensures accurate and affordable measurement of the unsaturated hydraulic conductivity of any soil (Decagon, 2018). It was used in this study because calculated values of hydraulic conductivity for various soils have excellent agreement with theoretical results (Zhang, 1997b). The instrument has a length of 32.7 cm, a diameter of 3.1 cm, length of suction regulation tube of 10.2 cm and a suction range of 0.5 – 7 cm. Based on the recommendations of Decagon (2018), a suction of -2 cm was selected for all readings in this study. The minidisk has two chambers (upper and lower) which were filled with water, while the lower chamber contains a volume of water that infiltrates into the soil at a rate determined by selected suction, the upper chamber controls the suction. Once placed on the soil, infiltration from the lower chamber begins, after every 30 seconds, readings of the new water volume in the lower chamber were recorded, and this was done for 300 seconds. The time span of 300 seconds was chosen based on the suggestion of Decagon (2018), and secondly, it was thought this time would allow a minimum of 15 – 20 ml of water to infiltrate into the soil during each measurement. This minimum value of infiltrated water is required to ensure accurate measurement of hydraulic conductivity (Decagon, 2018). To ensure a smooth contact with the soil, the minidisk was placed on a thin layer of sand spread on the soil. Excess contact sand outside the rim of the infiltrometer was swept away immediately after emplacing the infiltrometer on the thin sand layer so as to avoid any horizontal wicks of sand lying across the soil surface. Hydraulic conductivity k was estimated from cumulative infiltration measured in the field at a suction of -2 cm according to Eqs. 3.5 (Zhang, 1997a, b),

$$k = \frac{C_i}{A} \qquad \textit{Eq. 3.5}$$

where k (mm) = hydraulic conductivity

C_1= is the slope of the curve of the cumulative infiltration versus the square root of time, and A = a dimensionless coefficient relating the van Genuchten parameters for a given soil type to the suction rate and radius of the Infiltrometer disk. In this study, the value of A = 1.73 for sand and 3.91 for sandy loam were chosen to represent the soils in the area (Decagon, 2018).

Soil moisture was measured to determine the water retention capacities of the soils, which could in turn influence infiltration and surface runoff. To measure soil moisture, a Delta-T ThetaProbe ML2x Soil Moisture sensor was used to collect soil moisture readings. The Delta-T ThetaProbe ML2x measures volumetric soil moisture content (θ_v), by the method of responding to changes in the apparent dielectric constant, which is proportional to soil moisture content. Volumetric soil moisture content is the ratio between the volume of water present and the total volume of the sample. This is a dimensionless parameter, expressed either as a percentage (%vol), or a ratio ($m^3 .m^{-3}$) (Holzman et al. 2017; User manual, Delta-T 1999). Soil moisture readings were collected having inserted the probe into the soil until the rods were fully covered, that is to a depth of 6 cm. To avoid reduction of soil moisture value by air pockets, re-insertion of probe into same location (in the case of void reading during initial insertion) was avoided. Six readings were planned for both soil moisture and infiltration in each of the five visited community at the three identified land use classes, thus making it 18 readings per community.

During fieldwork, farming techniques were observed and recorded to relate what was observed in the field with changes in gully characteristics.

b). Local knowledge of gully-causing factors

While the use of geomorphic techniques to study gully evolution provides answers to mechanism of gully expansion, some information may not be readily available through this technique. For example, dates of gully initiation, forcing activities that led to gully formation as well as local knowledge on gully-landslide interactions. The significance of incorporating local knowledge is threefold: First, to eradicate any form of mistrust for science on the part of local population. Secondly, incorporating local knowledge provides for comparison of scientific understanding, hypotheses, forecasts, and arguments with prevailing local expertise, thus, enriching scientific findings. This second significance forms part of the public debate model proposed by Callon (1999). Finally, to avoid the adoption of non-native “top-down” approaches which are not effective in many instances in solving local environmental problems (van Aalst et al. 2008).

Focus group meetings were used to understand the dates of gully initiation, their dynamics of evolution over these years and efforts made by the community to reduce gully impacts. Two focus group meetings were held, each had 10 community leaders comprising men and women. Agendas for the meeting were organised into five: hazard identification, hazard mitigation, vulnerability and exposure, risk communication and factors constraining risk mitigation. Before the start of meetings, the elders were asked to give a history of the gully from when it started until the present day and this availed the opportunity to ask follow-up questions about forcing factors and mode of evolution. Questions included “what do you think causes gullying”? “Tell me what has been done to reduce gullying in your community”. Findings were presented using themes representing key results.

3.2.2 Objective 2: Effects of land-use changes on gully catchment hydrology

To achieve objective 2, the following research questions were posed:

1. Have there been changes in the hydrology of gully catchments between 2009 and 2018 in response to land-use changes?
2. Are there associations between changes in gully catchment hydrology and gully sizes?

3.2.2.1 Changes in gully catchment hydrology between 2009 and 2018 in response to land-use changes

The current research aims to understand hydrological responses to land-use changes, as well as evaluate how land-use configuration affects hydrological responses. Both surface and sub-surface flows propagate gullying and land-use changes affect both hydrological processes. Surface runoff from the upper segments of a catchment can flow to the lower segments if such a catchment is structurally connected, thus, surface runoff from the upper segment can enhance gullying farther from the point of runoff generation. Gullying is a continuous process and to understand gully responses to hydrological drivers, hydrological responses to land-use changes and data on catchment flow responses to catchment connectivity are needed in a continuous form. However, these required data are not available in the study area and thus, hydrological modelling was undertaken. Although many models exist (Table 3.6), while some do not proffer solutions to the data needs enumerated above, others are not suitable for the study area. For example, the TOPMODEL represents a simple approach to predicting spatial patterns of responses in a catchment and is premised on two basic assumptions; the dynamics of the saturated zone can be approximated by successive steady state representations of the saturated zone on an area '*a*' draining to a point on a hillslope, and that the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope measured with respect to plan distance (Beven, 2011). Areas prone to development of perched water tables are difficult to model with the TOPMODEL (Beven, 1997; 2011), but landslide events in southeast Nigeria have been attributed to the development of perched water tables (Akpan et al, 2015). The Soil and Water Assessment Tool (SWAT) model was chosen in this study over other models. Although SWAT is usually used for river basin assessments, the following make the SWAT model ideal in this study.

1. It is capable of modelling both surface and sub-surface flow responses to land-use changes.
2. The model can simulate hydrological responses to land-use configuration.
3. SWAT is a continuous model.
4. SWAT can model agricultural activities such as tillage (farming is the predominant activity in rural Nigeria).
5. The model has available GIS user-friendly versions.

The most evident indication of hydrologic change within a catchment is from the trend of surface runoff (Anand et al, 2018), assumptions of the runoff method used in SWAT are presented in section 3.2.2.1.4. The primary limitation of using this model is the inability to estimate rainfall intensity and event-based floods. In section 2.2.1, rainfall intensity was identified as a potential driver of gullying in southeast Nigeria, however, unavailability of this data is one of the uncertainties of this study.

Table 3.6: Examples of hydrological models. The SWAT model was chosen in this study due to the points listed above.

Model	Strengths	Suitability for study	Reference
TOPMODEL	Can be applied in small catchments (<2 km^2) in the humid tropics.	Areas prone to development of perched water tables are difficult to model with the TOPMODEL	Campling, et al. (2002). Beven, 1997; 2011.
SWAT	Continuous, can reflect hydrological responses to land-use changes	Inability to simulate event-based processes	Spruill et al, 2000. Arnold et al, 1998
Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS)	Can simulate the impact of land management on water, sediment, nutrients, and pesticides leaving the edge of a field.	Unable to model hydrological responses to catchment connectivity	Knisel, 1980, Crowder et al, 1985
Precipitation Runoff Modelling System (PRMS)	Watershed response can be simulated at both a daily and a storm time scale	Unable to model hydrological responses to catchment connectivity	Leavesley & Stannard, 1995
MIKE SHE	Able to simulate surface and sub-surface processes	Requires huge amount of data	Zhang et al, 2008, Arnold et al, 1998.

3.2.2.1.1 The SWAT Model

SWAT is a hydrologic/water quality model developed by United States Department of Agriculture - Agricultural Research Service (USDA-ARS) (Arnold et al. 1998). It is a physically based model, designed with the objective of predicting the impact of land-management practices on water, sediment, and agricultural chemical yields in watersheds with varying soil, land use, and management conditions (Santhi et al. 2001; Neitsch et al. 2012; Dile & Srinivasan, 2014). The SWAT model can simulate hydrological processes with a daily time step by disaggregating a catchment first into sub-basins and further dividing sub-basins into Hydrological Response Units (HRUs), (Dile & Srinivasan, 2014). A HRU is a lumped land area within a sub-basin that consists of homogeneous land use, management, topographical, and soil characteristics. The HRUs are represented as a percentage of the sub-basin area and may not be contiguous or spatially identified within a SWAT simulation (Arnold et al. 2012). The focus of the present research is on the impacts of land-use changes on hydrological responses within gully catchments and by extension, how these impacts affect gullying, thus, making SWAT an ideal model in this study.

Water balance is the primary basis behind SWAT because of its impacts on sediment transportation as well as plant growth (Arnold et al. 2012). Simulation of watershed hydrology is divided into two: the land (representing the hillslope) and in-stream/routing components. First, the land component controls the amount of water and sediment loadings into the main channel in each sub-basin. The following hydrologic processes are simulated by SWAT: canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels. Secondly, movement of water through the channel network to the watershed outlet is controlled by the in-stream/routing component (Arnold et al. 2012). There are different versions of the model; the 2012 version is used in this study because it has the ArcGIS interface. The following sub-sections detail the working mechanism and required data for the SWAT model.

3.2.2.1.2 The Weather data and Weather Generator

Weather data are required to estimate hydrological processes using the SWAT model. Daily rainfall, minimum and maximum temperature, solar radiation, mean daily wind speed and relative humidity are the needed weather parameters. Where these parameters are available, they are read-into the model and used for model runs. Due to the unavailability of these data on a daily time scale in the study area, the inbuilt SWAT weather generator was used. The SWAT model generates daily values for weather for individual sub-basins based on average monthly values summarised over a number of years and there is no spatial correlation of generated values between different sub-basins (Neitsch et al. 2011). These monthly weather averages were provided by the Climate Forecast System Reanalysis (CFSR) global meteorological database for latitudes 5° & 6° N and longitudes 6° and 7° E. Initial exploration of other data sources (The Tropical Rainfall Measuring Mission and The European Centre for Medium-Range Weather Forecasts-ERA5) was undertaken but downloaded climate data gave wrong readings for the study area. CFSR weather data were produced with data-assimilation techniques (both conventional meteorological gauge observations and satellite irradiances) as well as highly advanced atmospheric surface modelling components at ~ 34 km resolution

(Saha et al. 2010; Dile & Srinivasan, 2014). CSFR weather data span between 1979 and July 2014. Figure 3.4 shows simulated weather stations used to generate weather parameters in the study area.

3.2.2.1.3 Potential and actual evapotranspiration

Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from an area uniformly covered with growing vegetation that has access to unlimited supply of soil water and that was not exposed to advection or heat storage effects (Thornthwaite, 1948) while actual evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapour (Neitsch et al. 2011). Evapotranspiration is a dominant process by which a watershed loses water (Neitsch et al. 2011). To calculate actual evapotranspiration, PET, is first simulated.

The Penman-Monteith method of calculating PET was used in this study, it provides an accurate estimate of Potential Evapotranspiration on daily time scales (Allen et al. 2006). This method of estimating evapotranspiration requires solar radiation, air temperature, relative humidity and wind speed, these weather variables were generated using CSFR weather generator for the study area. The full form of the Penman-Monteith evapotranspiration equation is given in Equation 3.6, (Neitsch et al. 2011),

$$\lambda E = \frac{\mathit{\Delta}(R_n - G) + P_a C_P\,(e_s - e_a)/r_a}{\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)} \qquad \textit{Eq. 3.6}$$

Under neutral atmospheric stability, Equation 3.6 can be written as,

$$\lambda E_t = \frac{\mathit{\Delta}(R_n - G) + \gamma . K_1(0.622 . \lambda . P_a/P)\,(e_s - e_a)/r_a}{\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)} \qquad \textit{Eq. 3.7}$$

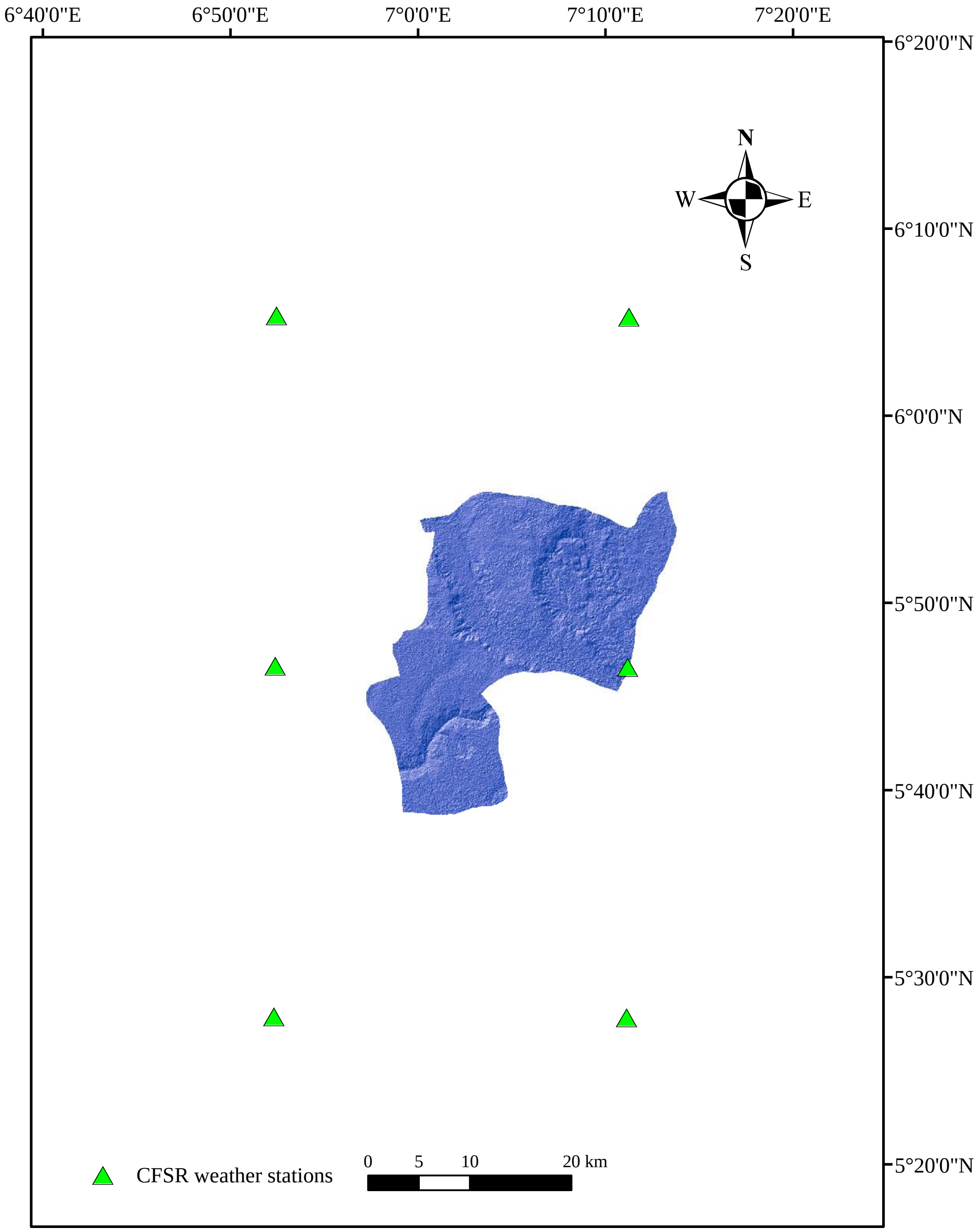


Figure 3.4: Climate Forecast System Reanalysis (CSFR) simulated weather stations used for generating weather data.Also shown is the shaded relief map of the study area

Where λE = latent heat flux density (MJ m^{-2} d^{-1}), E = depth of evaporation (mm day^{-1}) Δ = slope of the saturation vapour pressure versus temperature curve (kPa/°C), R_n= net radiation flux density at the surface (MJ/m^2/day), G = sensible heat flux density from the surface to the soil (positive if the soil is warming) (MJ/m^2/day), P_a= air density (kg m^{-3}), C_P = specific heat of moist air at constant pressure of air (MJ kg^{-1} °C^{-1}), e_s = saturation vapour pressure at air temperature (kPa), e_a = actual vapour pressure of the air (kPa), r_a = aerodynamic resistance to turbulent heat and/or vapour transfer from the surface to some 'z' height above the surface (s m^{-1}), γ = pyschrometric constant (KPa/°C), r_s = bulk surface resistance that describes resistance to flow of water vapour from inside the leaf, vegetation canopy or soil to outside the surface (s m^{-1}), λ = latent heat of vaporization (MJ kg-1), E_t = maximum transpiration rate (mm d-1), K_1= dimension coefficient needed to ensure the two terms in the numerator have same units ($8.64 * 10^4$ ms^{-1}), P = atmospheric pressure (kPa).

To calculate actual evapotranspiration, SWAT first evaporates any rainfall intercepted by plant canopy, then maximum amount of transpiration and soil evaporation is completed (Neitsch et al. 2011).

Maximum amount of water that can be held in canopy storage varies from day to day as a function of the leaf area index (LAI):

$$can_{day} = can_{max} \cdot \frac{LAI}{LAI_{max}}$$

Eq. 3.8

Where can_{day} = maximum amount of water that can be trapped in the canopy on a given day (mm H_2O), can_{max} = maximum amount of water that can be trapped when the canopy is fully developed (mm H_2O), LAI = leaf area index, LAI_{max} = maximum leaf area index for the plant. Maximum leaf area index used in the study area are 4 and 5 m^2/m^2 for cassava and evergreen forests respectively. Influence of plant on rainfall interception is a function of plant density cover and morphology of plant species (Neitsch et al. 2011). When using the Penman-Monteith method in SWAT, actual transpiration is calculated using Equation 3.7, and Maximum amount of soil evaporation on a day is calculated using Equation 2:2.3.7 of Neitsch et al. (2011):

$$E_S = E_o'.cov_{sol}$$

Eq. 3.9

Where E_S = maximum soil evaporation in a day (mm H_2O), E_o' = potential evapotranspiration adjusted for evaporation of free water in canopy (mm H_2O), cov_{sol} = soil cover index.

$$cov_{sol} = \exp(-5.0 * 10^{-5}.CV)$$

Eq. 3.10

Where CV = aboveground biomass and residue (kg ha^{-1}).

3.2.2.1.4 Runoff generation

Surface runoff in SWAT is estimated separately for each sub-basin and routed to obtain the watershed total runoff value (Dile & Srinivasan, 2014). Two methods are available for simulating runoff using the SWAT model: The Curve Number (CN) and Green and Ampt infiltration method. While the Green and Ampt method requires sub-daily rainfall data, the CN approach uses daily rainfall data, but the SWAT model generates rainfall data on a daily time step. Apart from the unavailability of sub-daily rainfall data in the study area, the CN approach is adopted in the present study because:

a) The background to the curve number is purely empirical, that is primarily its strength (Beven, 2011).
b) The CN is responsive to major runoff-producing watershed properties (soil, land use/treatment, surface condition and antecedent condition) (Ponce & Hawkins, 1996).

The CN is an abstraction parameter which varies between 1 and 100, with 1 being full abstraction and zero runoff and 100 being no abstraction, which means all rainfall resulted in surface runoff. This method of estimating runoff is essentially based on the water balance equation (Equation 3.11) and on a fundamental hypothesis which states that the ratio of actual retention to potential retention is equal to the ratio of actual runoff to potential runoff as represented in Equation 3.12 (Kandissounon et al. 2018), this assumption underscores the conceptual basis of the runoff curve number method (Ponce, 1989).

$$P_i = I_a + F + Q$$ Eq. 3.11

$$\frac{Q}{P_i - I_a} = \frac{F}{S}$$ Eq. 3.12

$$Q = \frac{(P_i - I_a)^2}{P_i - I_a + S}$$ Eq. 3.13

where P_i = rainfall (mm), I_a = initial abstraction (mm), F = cumulative infiltration without initial abstraction (mm), Q = runoff (mm), S = maximum potential retention (mm).

The basic form of the Curve Number is represented in Equation 3.13 which is obtained by combining equations 3.11 and 3.12 (Kandissounon et al. 2018). Equation 3.13 is physically subject to the restriction that $P_i \geq I_a$ (i.e. the potential runoff minus initial abstraction cannot be negative) (Ponce, 1989). Initial abstraction, I_a, is related to potential maximum retention, such that,

$$I_a = 0.2S \qquad \text{Eq. 3.14}$$

Thus, substituting 3.14 in 3.13, Equation 3.15 is derived.

$$Q = \frac{(P_i - 0.2S)^2}{(P_i + 0.8S)} \qquad \text{Eq. 3.15}$$

Equation 3.15 is subject to $P_i \geq 0.2\mathrm{S}$.

The CN is a function of a) hydrologic soil type, b) land use c) antecedent moisture condition (Ponce, 1989). Soils are classified into four hydrologic types; A, B, C and D. Hydrologic groups A and B have higher infiltration capacities, while C-group have a lower infiltration capacity. Soils in group D have high runoff potential. Table 3.7 shows the hydrological groups of soils in the study area. Land use classification has been described in Section 3.2.1.1. For estimating runoff in SWAT, non-vegetated areas were classified into three categories identified by the SWAT model: Urban High Density (URHD), Urban Low Density (URLD) and Urban Medium Density (URMD). These classifications were based on visual interpretation of cluster/connectedness of built-up areas in the land-use maps, as well as observations during fieldwork. Gully catchments with highest connectedness were assigned Urban High Density and the least connected catchments were classified as Urban Low Density. Open vegetation classification refers to farms and grassed areas. Cassava (*Manihot esculenta*) is the dominant crop (Ande et al. 2008; Ozor et al. 2010), hence, cassava was input in the open vegetation class. Evergreen forest was selected to represent tree land-use class.

Table 3.7: Hydrological soil groups for different soils in the study area and corresponding Antecedent Moisture Content Curve Numbers.

Soil	Hydrologic soil group	Land use	CN		
			AMC 1	AMC 11	AMC 11
Nd19-1a-1557	B	URLD	43.9	63.3	81.0
		URBN	55.5	73.8	88.0
		URHD	66.2	82.4	92.8
		CASS	59.3	77.0	89.9
		FRSE	35.3	55.0	74.5
Nd21-1a-1560	B	URLD	43.9	63.3	81.0
		URBN	55.5	73.8	88.0
		URHD	66.2	82.4	92.8
		CASS	59.3	77.0	89.9
		FRSE	35.3	55.0	74.5
Ph17-1a-6596	A	URHD	54.3	72.8	87.4
		CASS	47.9	67.0	83.7
		FRSE	15.1	35.0	54.2

Three classes of Antecedent Moisture Condition (AMC) are identified by the CN and they are AMC I, AMC II and AMC III. These conditions correspond to dry, average and wet conditions respectively. AMC I (dry) is defined as when the cumulative rainfall in the previous five days is < 13 mm, and AMC III (wet) is defined as when cumulative rainfall for the previous five days is > 28 mm (Liu et al. 2019). When the cumulative rainfall is between 13 and 28 mm, it is considered as AMC II (average) (Liu et al. 2019). In HRUs with urban areas, the SWAT model adjusts the CN number to reflect the impact of the impervious areas (Neitsch et al. 2002)

3.2.2.1.5 Flood routing

The flood-routing model uses a variable storage coefficient technique developed by Williams (1969) such that for any given reach segment, storage routing is based on the continuity equation:

$$\Delta V_{stored} = V_{in} - V_{out} \qquad \textit{Eq. 3.16}$$

Where ΔV_{stored} = change in volume of storage during the time step (m^3 H_2O), V_{in} = volume of inflow during the time (m^3 H_2O), V_{out} = volume of outflow during the time step (m^3 H_2O).

3.2.2.1.6 Channel characteristics

Channel length, slope, width, depth, and Manning's -'n'- are input required by SWAT. The channel length is the distance along the channel from the sub-basin outlet to the most distant point in the sub-basin, while channel slope is computed by taking the difference in elevation between the sub-basin outlet and the most distant point in the sub-basin and dividing by channel length. Both the channel length and slope can be accurately estimated using the DEM (Ames et al. 2009; Han et al. 2019). Channel width, depth and Manning's -'n'- were manually entered into the model. Channel width was computed by developing a new regression equation similar to that used by SWAT to calculate channel width (Equation 3.17).

$$W_{bnk\,full} = 1.29. A^{0.6} \qquad \textit{Eq. 3.17}$$

where $W_{bnk\,full}$ = bankfull width of main channel (m), A = upstream drainage area (km^2).

To develop a new regression equation, the drone image (section 3.2.1.2) of Urualla gully catchment was used. First, the Urualla catchment was delineated and sub-basin area (km^2) calculated. Then using the drone image, the widths of sub-basin channels were identified and measured. A linear regression was calculated for measured channel width (m) and SWAT-calculated upslope contributing areas of the sub-basins (km^2) (figure 3.5). The new regression equation was developed as a Power Law function of the upslope contributing area, Equation 3.18. This new regression equation was used to calculate channel widths for the gully catchments. Manning's -'n'- of 0.03 was adopted in this study and this value was selected based on the recommendations of Chow, (1959).

$$w = 2.56. A^{0.78} \qquad \textit{Eq. 3.18}$$

where w = channel width (m), A = upslope contributing area (km^2). Equation 3.18 ($r^2 = 0.70$, adjusted $r^2 = 0.68$, p-value < 0.05) was used to calculate channel width in this study.

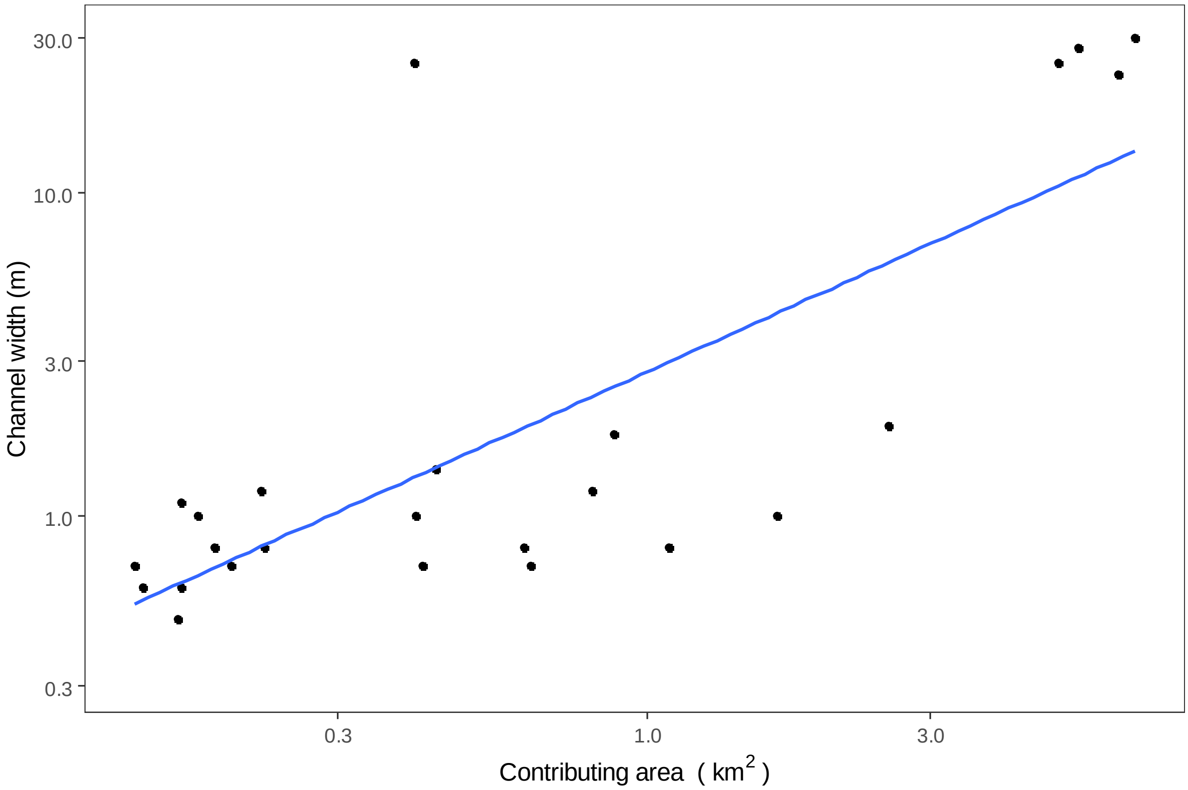


Figure 3.5: Channel width vs contributing area relationship developed for the study area

3.2.2.1.7 Data requirement for SWAT

To run the SWAT model, the following datasets are required.

I. Topography

Topographic data used in this study were the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at 30 m resolution acquired from the United States Geologic Survey (USGS). The DEM was used to delineate gully watersheds in ArcSWAT and create stream networks of the catchments. To delineate a gully watershed, a pour point was identified at the end of the gully such that the model was able to define the watershed contributing flow through the pour point. SWAT uses single flow algorithm to define catchments.

II. Soil

Soil data were acquired from the Digital Soil Map of the World (DSMW) prepared by the Food and Agricultural Organisation using the topographic map series of the American Geographical Society of New York as a base at a nominal scale of 1:5 000 000. This map was supported by particle-size analysis (PSA) of soils in the study area (section 3.2.1.3). To support the DSMW classification, average particle size results for the different textural components in sampled communities were used. Using the soil in Isu Njaba community as an example, four soil samples were collected, and PSA results derived for these four samples. The average values for sand, gravel and fine materials in this community was input into the soil texture triangle for appropriate texture classification. The DSMW classified soils in Isu Njaba as sandy-loam, while average particle size results for the four sampled sites also classified the soils as sand-loam, thus, PSA results were used to authenticate the DSMW which has a coarse resolution. The usersoil-database in SWAT holds physical characteristics of different soils, three soil types (Table 3.7) were identified for the study area and used to run the SWAT model.

III. Land-use maps

Land-use maps for 2009, 2014 and 2018 for the study area were input into the model. While 2009 and 2018 maps covered the entire study area, the 2014 map covered some gully catchments.

3.2.2.1.8 Model setup

Multiple HRUs were created in each sub-basin using the soil, topography and land-use maps. A zero percent threshold was used in creating the HRU, ensuring that all land use and soil types as well as all slope classes were considered in creating the HRUs. No reservoirs were defined as there were none in all the gully catchments. Management-practice data are needed to run the SWAT model and they include planting, harvesting and killing, tillage, and fertilizer and pesticide applications. The planting season starts at the beginning of rainy season, ending of March-beginning of April (Onwuka et al. 1997; Nya et al. 2010), hence, March 28 was selected as planting start date and December 28 for harvest/kill. Tillage distributes nutrients, pesticide, and residue in the soil profile. The hoe is the traditional tilling tool used in the study area. The depth of tillage with the hoe is up to 100 mm and a mixing efficiency of 0.3 was selected based on the suggestions of Neitsch et al. (2011). Application of chemical fertilizers and pesticides is not common among non-commercial farmers. The farmlands under investigation in this study are non-commercial, where chemical fertilizers were not applied. Plant growth in SWAT can be scheduled by fraction of potential heat units or by day. Plant growth cycle is controlled by plant attributes summarised in the plant growth database and by timing operations contained in the management-practice (Neitsch et al. 2011). Since the planting season is known for cassava, growth was scheduled by day for cassava. Having set up the model, a warm-up period of two years was selected for the model run.

3.2.2.1.9 Model output used

Gully erosion is driven by surface and sub-surface processes (section 2.1) hence surface runoff, lateral flow, groundwater flow and streamflow were the model outputs of interest. Changes in these modelling output over the years were related with changes in gully sizes. Trends and changes were identified in two parts: between 2009 – 2014 and 2014 – 2018 for catchments covered by the 2014 satellite imagery, and between 2009 – 2018, for gully catchments covered by the 2009 and 2018 satellite data.

3.2.2.1.10 Model application in different settings

To understand the extent to which land-use changes alone affected changes in catchment hydrology, an 'exploratory sensitivity analysis' was conducted. The 2009 rainfall was applied to land-use maps of 2009 and 2018 in Amucha and Orlu1 catchments. Rainfalls for 2009 and 2018 were also applied to the land-use maps of 2009 in Amucha and Orlu1 catchments. This step was undertaken to ascertain the influence of changes in rainfall on catchment hydrology.

3.2.2.1.11 Result validation

Validation is a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model (Sargent, 1984; Curry et al. 1989). This demonstration indicates that the model is acceptable for use, not that it embodies any absolute truth (Oreskes et al. 1994; Rykiel, 1996). While it is commonplace to validate SWAT models using statistical techniques by testing levels of agreement between observed and estimated results (e.g. Fuka et al. 2014; Dile & Srinivasan, 2014), other methods such as face validity, exist for validating models (Rykiel, 1996). The validation process shows that a model meets some specified performance standard under specified conditions and embodies three conditions (Rykiel, 1996):

A. The model is in accord with the facts (data) as we know them at the time,
B. What is true or accepted as true in ecology (based on our judgment),
C. The model is justifiable and appropriate for our purposes.

There are no observed streamflow data in the area of study and hence modelled results were not validated using statistical tests of agreement between observed and estimated values, rather, three methods: use of literature review, observations during field work and data obtained from respondents during focus group meetings, were used for validation.

3.2.2.1.12 Associations between changes in gully catchment hydrology and gully sizes

Changes in modelling output for the study years were identified. These variations in values were related to changes in gully sizes. Identified trends and differences were used to infer likely associations between changes in gully catchment hydrology and changes in gully sizes.

3.2.3 Objective 3: Effects of changes in land use on gully-landslide interactions

To achieve objective 3, a research question was posed: How will changes in land use and catchment hydrology affect gully-landslide interactions? To answer this question, identifications of gully-induced landslides and landslide-induced gullying in the field were necessary.

3.2.3.1 Gully-induced landslides

During fieldwork, old and fresh gully-induced landslide scars were identified and documented. Coordinate points of identified landslides were acquired using the hand-held GPS. Other landslide attributes (runout distance, depth, slope angle) were also collected. Runout distance and slide depths were measured using a tape measure (Surveyor's 30 m tape) while a clinometer (PM-5 SUUNTO model) was used to measure landslide slope angle. Landslide attributes (slope and depth) were used for stability and sensitivity analyses of gully walls. Recent landslides were identified based on the suggestions of Lee (2005): breaks in the forest canopy, bare soil, or other geomorphic characteristics typical of landslide scars, for example, head and side scarps, flow tracks, and soil and debris deposits below a scar. Older slides were visible in the form of scars.

3.2.3.2 Slope stability analysis

Slope stability is usually expressed in terms of factor of safety (FoS) which is traditionally defined as the ratio of actual soil shear strength to the minimum shear strength required to prevent failure (Dawson et al. 1999). Different types of slope failure can be computed using different stability models, e.g. Istanbulluoglu et al, (2005) used the Channel-Hillslope Integrated Landscape Development (CHILD) model to investigate effects of slab failures on the tempo of landscape evolution and resulting landscape morphology. They found that under dry conditions, the maximum gully height before slab failures occurred were 1.6 m, 3.2 m and 6.4 m for the respective soil cohesion values of 5 kPa, 10 kPa and 20 kPa. Thus, low soil cohesion resulted in rapid valley widening by small failures and high rates of soil loss (Istanbulluoglu et al, 2005). Shallow translational slides are prevalent in southeast Nigeria

(Igwe et al. 2014) and stability analysis for this type of slope failure can be computed using the infinite slope model, represented in Equation 3.19 (Selby, 1993).

$$F = \frac{\mathrm{c} + (\gamma - \mathrm{m}\gamma_w)\, z\cos^2 \beta \tan\varphi}{\gamma z \sin \beta \cos \beta} \qquad \textit{Eq. 3.19}$$

where

c = cohesion (kN/m^2)

z = vertical thickness of the material above plane of failure (m)

γ = specific weight of the soil (kN/m^3)

γ_w = specific weight of water (kN/m^3)

β = slope angle (°)

$\tan\varphi$ = friction angle of material (°)

m = height of the water table above plane of failure; expressed as a fraction of the vertical thickness of the material so that m = 1.0 if the water table is at ground surface and m = 0 if the water table is at or below the plane of failure.

In using the infinite slope model, the plane of failure is assumed to be at a constant depth beneath the surface along the slope and the slope mantle is assumed to be uniform along the slope. Therefore, the stability of a single column of soil, of unit lateral dimensions, should be a reasonably accurate indicator of stability of the slope as a whole (Carson and Kirkby, 1972). During fieldwork, shallow slides were observed in visited gullies in Amucha and Urualla, while block failure was observed in Obibi-Ochasi. While the infinite slope model is adequate to understand shallow slides, it may not be appropriate for other types of landsliding e.g. block failure, hence, in this project, Equation 3.19 is exclusively used to understand shallow landslides observed in Amucha and Urualla only. Susceptibility of the gully wall to the block failure observed in Obibi-Ochasi was not modelled using the infinite slope model. Geotechnical results of soil samples collected from landslide sites within the Amucha gully complex (Table 3.5) were used in Equation 3.19 for stability analysis of the gully. Slope angles of identified gully-induced slides were measured using clinometers.

3.2.3.3 Sensitivity analysis for slope stability

A sensitivity analysis involves keeping the value of all model parameters constant, reducing the value of one parameter, and seeing if the resultant model predictions change and can be readily achieved using either real or synthetic data (Zhang et al. 2002). This analysis is relevant as it helps a model user understand the strengths and contributions of all the parameters used within a model, and thus make informed decisions about practical applications of their model. To test sensitivities of parameters in Equation 3.19, slope values from the Urualla drone survey (section 3.2.1.2) were used as slope input while other parameters were sourced from the geotechnical results of the Amucha soil samples.

3.2.3.4 Landslide-induced gullying

Landslide-induced gullying was inferred following observations made during fieldwork and analysis of gully-pictures. Presence of landslide scars which could promote rill-formation and further enlarge gullies were observed and documented. These data sources were used to make inferences about the role of landslide scars as gully-drivers.

3.2.3.5 Effects of changes in land use and gully catchment hydrology on gully-landslide interactions

Observed results from section 3.2.1 and modelled results from section 3.2.2 in addition to published studies were used to understand effects of changes in land use and gully catchment hydrology on gully-landslide interactions.

3.2.4 Objective 4: Resultant hazards and effects of gully-landslide interactions in affected communities

To achieve objective 4, two points are important: First, awareness of hazards accruing from gully-landslide interactions, secondly, ability to identify likely effects of these hazards. Therefore, the following research questions are asked:

1. What is the perception of local population to gully-landslide hazards?
2. What are the effects of gully-landslide interactions on affected communities?
3. What control measures have been adopted by communities to reduce effects gully-landslide interactions?

To provide answers to these research questions, qualitative data collection and analysis techniques were adopted. This part of the methodology was also used to understand local knowledge on gully-landslide interactions and is divided into three:

a. Use of structured questionnaire: Two communities, Amucha (Njaba LGA) and Obibi-Ochasi (Orlu LGA) were selected for questionnaire survey, this selection was guided by a published document of Imo State Government (1983) which identified gullies in these communities as the biggest and most active in the State. Based on the population of the LGAs, 96 copies of questionnaire were distributed to each community representing the LGA, this figure was arrived at by using an online version of The Survey Software. The survey software calculates sample size using the following equations,

$$ss = \frac{Z^2(P) * (1 - P)}{C^2} \qquad \textit{Eq. 3.20}$$

where:

ss = sample size
Z = Z value (e.g. 1.96 for 95% confidence level)
p = percentage picking a choice, expressed as decimal
c = confidence interval, expressed as decimal

The sample sizes were calculated by choosing a confidence interval of 10 at 95% confidence level for a 2018 population estimate of 210,614 for Njaba and 209,597 for Orlu LGAs respectively. Population was estimated from the 2006 census figures of the LGAs at an annual growth rate of 3.25%. Questions were organised in four sections; “A” was on hazard awareness and had questions for example “do you think landsliding can cause harm”? Section “B” focused on hazard impacts with questions such as “how many houses/property have been lost in this autonomous community to gully erosion in the last 10 years”? Section “C” focused on control measures and contained questions for instance “as an individual, what have you done to reduce hazard impacts of gullying”? Finally, information on demographics were collected in section “D”. Copies of the questionnaire were given to adults only.

b. Focus group meetings: this method of data collection has been discussed in section 3.2.1.3.

c. Informal interview sessions: These were non-structured and were conducted with the local guides and interviewees during site visits and were site-specific. For example, a community like Amucha has a non-profit local NGO and volunteers tasked with planting trees and guiding researchers around the Amucha Gully. Site specific questions included "what year was this NGO formed"? In Urualla where gullying has led to silting and complete disappearance of a stream, questions were asked including "what year did the stream disappear"? "What do you think caused the disappearance?"

Responses from this part of the methodology were organised in themes which represented the key findings of this section of the research.

3.3 Chapter summary

This chapter has presented the methods used in this study as well as justifications for choosing these methods. Combinations of community-based knowledge of gully-causing factors, analysis of remotely sensed data, quantitative methods, geotechnical survey and hydrological modelling improved the results of the present research. Chapter 4 presents findings on analysis of remotely sensed data, geotechnical investigation, results of quantitative methods and focus group meetings. This part of the methodology provides answers to objective 1. In chapter 5, I present results on SWAT modelling and relate changes in catchment hydrology with changes in gully sizes thereby solving questions raised by objective 2. Based on results of chapters 4 and 5, and supported by field observations, answers to objective 3 are achieved and are presented in chapter 6. In chapter 7, results of questionnaire survey, focus group meetings and interviews are used to answer questions raised by objective 4.

Chapter 4

Influence of land use and land-use changes on gully characteristics

4.0 Introduction

This chapter addresses objective 1, which is the Influence of land use and land-use changes on gully characteristics. Gully characteristics as used in this chapter refer to gully numbers, length, width, and area. In order determine the influence of land-use changes on gully characteristics (objective 1), it is necessary to establish the features of land-use changes in the study area and secondly, understand other factors that interact with land-use changes to influence gully characteristics. Therefore, the following research questions are posed:

1. What are the land-use classes in the study area?
2. Have there been land-use changes in the study area between 2009 and 2018?
3. Have gully characteristics changed between 2009 and 2018?
4. How have ecogeomorphic interactions (i.e. interactions between land-use changes and these other driving factors) affected changes in gully characteristics?

Section 4.1 presents results of land use classification and land-use changes between 2009 and 2018, in section 4.2, results of gully characteristics are shown. The influence of land use and land-use changes on gully sizes are presented in section 4.3. Section 4.4 describes results of other factors (e.g. slope, elevation, gully nearness to road and rivers) whose interactions with land-use changes affect gully characteristics. Discussion of the results is provided in section 4.5. Chapter summary and conclusions are presented in 4.6 and 4.7.

4.1 Land-use classification and land-use changes between 2009 and 2018

In the study area, land is either used for building, farming or left to fallow, hence, land use is classified into three classes: non-vegetated, open vegetation and fallow/trees using supervised classification (section 3.2.1.1). Figure 4.1 shows the land use classes. Non-vegetated refers to built-up/settled areas and bare surfaces, while open vegetation denotes grassed-areas and farmlands and fallow/trees refer to areas covered by trees and fallow. Cassava is the dominant food crop in the study area as was confirmed in some visited farms during the field visit covering 100% of land (Figure 4.2A). Mixed farming (e.g. maize, cassava, palm trees and yam could be found on same farm) is a common practice in the study area (Figure 4.2B). In 2009, non-vegetated class covered an area of 58.6 km^2, this number increased to 144.7 km^2 in 2018, thus an increase by 146.8%. Also, during this time, open vegetation class increased from 195.1

km^2 to 332.4 km^2, and there was a reduction in fallow from 281.2 km^2 in 2009 to 57.8 km^2 in 2018. These values translate to a percentage increase of 70.4 % and reduction of 79.5% for open vegetation and fallow classes respectively (Figure 4.3). Table 4.1 shows proportional changes among land uses. Of the 58.6 km^2 of non-vegetated lands in 2009, 10.9 km^2 was converted to open vegetation, while 0.18 km^2 was transformed to fallow in 2018. 120.2 km^2 of Open vegetated lands remained the same while 68.22 km^2 and 6.7 km^2 were converted to non-vegetated and tree/fallow-cover respectively between 2009 to 2018. 50.9 km^2 of fallow/tree-cover remained the same between 2009 and 2018 while 29 km^2 was converted to non-vegetated and 201.3 km^2 was used for open vegetation in 2018. Thus, highest conversions of land use were from tree/fallow class to open-vegetated class.

Table 4.1: Proportional changes among land uses. Diagonals represent portions of lands that have remained the same between 2009 and 2018.

	2018 Non-vegetated (km^2)	2018 Open-vegetation (km^2)	2018 Fallow/tree (km^2)
2009 Non-vegetated (km^2)	**47.52**	10.95	0.18
2009 Open-vegetation (km^2)	68.22	**120.2**	6.68
2009 Fallow/tree (km^2)	29	201.3	**50.91**

Accuracy assessments

Tables 4.2 and 4.3 show accuracy assessments for 2009 and 2018 land-use maps, respectively (section 3.2.1.1). Overall accuracy was 97% for 2009 and 93% for 2018, while the kappa statistics were 0.96 and 0.9 for 2009 and 2018, respectively.

Table 4.2: 2009 accuracy assessment showing high accuracy results for identified land use classes.

Overall accuracy (%): 97			Kappa statistics: 0.96		
Classified data	Non-Veg	Open veg	Trees	Reference total	User accuracy (%)
Non-Veg	29	0	0	29	100
Open veg	1	29	0	30	96.7
Trees	0	1	30	31	96.8
Classified total	30	30	30	90	
Producer accuracy (%)	96.7	96.7	100		

Table 4.3: 2018 accuracy assessment showing high accuracy results for identified land use classes.

Overall accuracy (%): 93			Kappa statistics: 0.9		
Classified data	Non-Veg	Open veg	Trees	Refernce total	User accuracy (%)
Non-Veg	29	0	0	29	100
Open veg	1	29	4	34	85.3
Trees	0	1	26	27	96.3
Classified total	30	30	30	90	
Producer accuracy (%)	96.7	96.7	86.7		

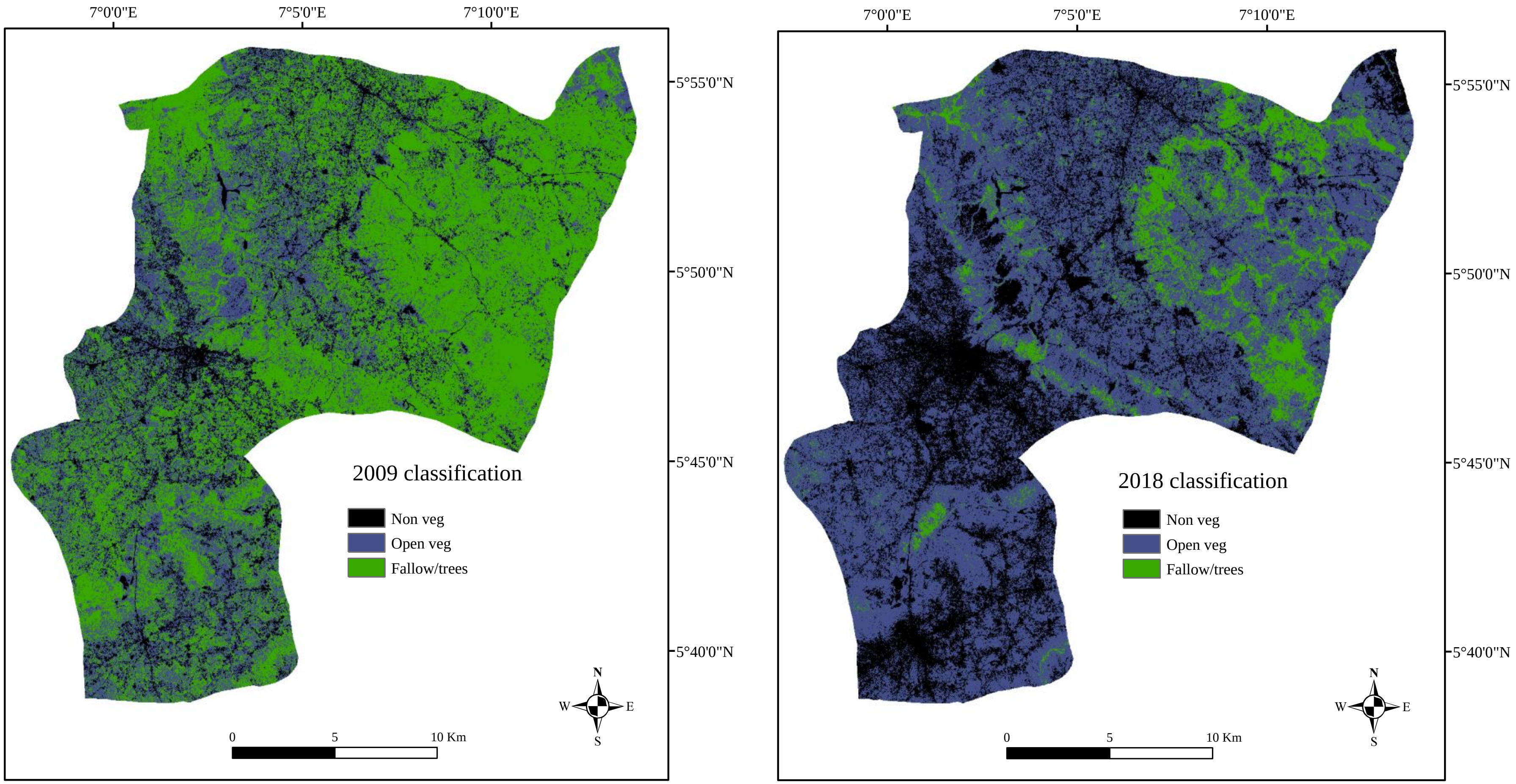


Figure 4.1: 2009 and 2018 land use classification maps, three classes of vegetation are shown, non-vegetated, open vegetation and fallow/tree-covered areas. There is increase in non-vegetated cover and reduction in fallowed areas in 2018.

Figure 4.2: A) Freshly planted cassava farm covering 100% of farm. Also shown is fallowed area at the edge of the farmland B) Mixed-cropped farm of cassava and palm plantation on the same farmland.

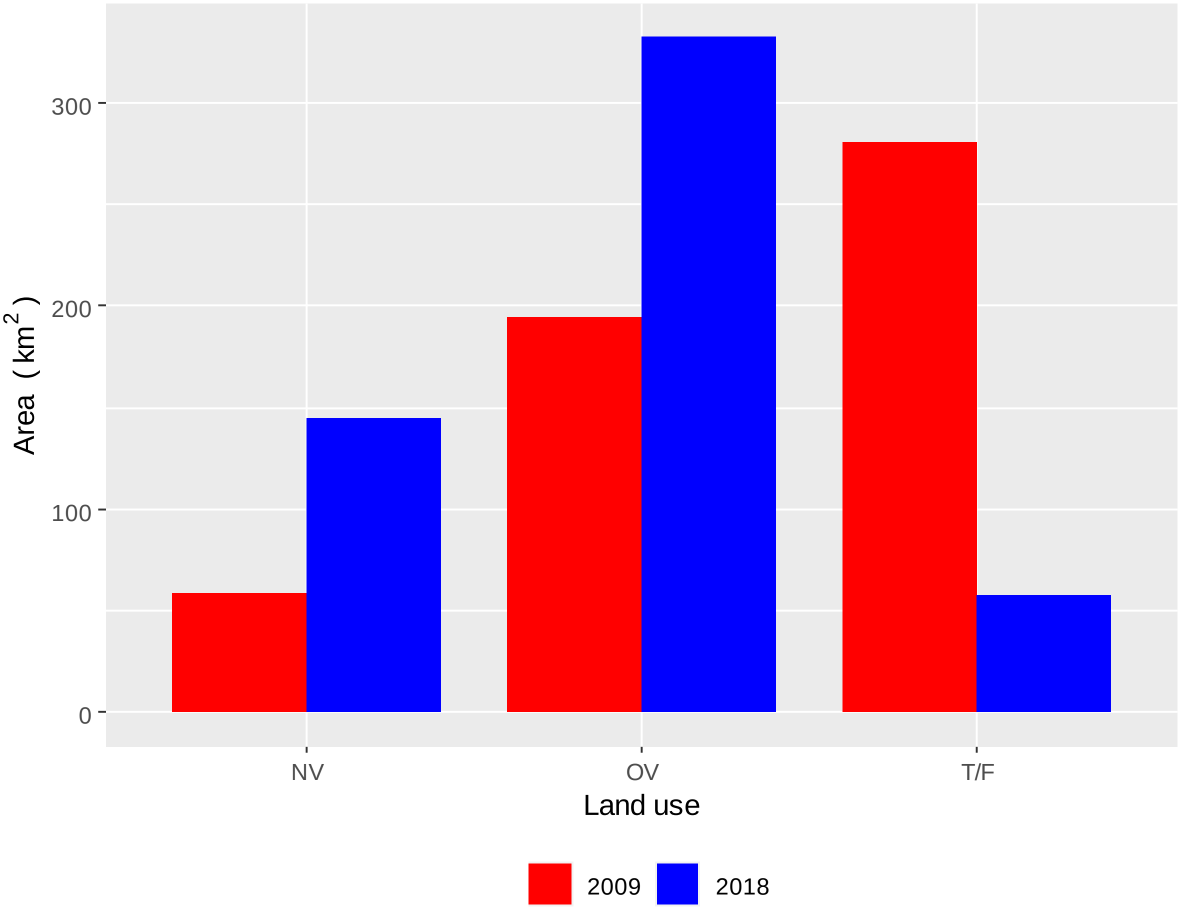


Figure 4.3: Land-use changes between 2009 and 2018. There is an increase in land areas under non-vegetated and open vegetation classes, while there was a reduction in fallow/tree covered lands in 2018. NV = Non-vegetated, OV = Open vegetation, T/F = Tree/Fallow.

Kappa statistics of > 80% show strong agreement and good accuracy, 40 – 80% is middle while < 40% is poor (Gwet, 2002; Appiah et al. 2018). Tables 4.2 and 4.3 indicate that there is good accuracy in the land-use classification for this study. It can be inferred from figures 4.1 and 4.3 that there have been major changes in land use between the years under review.

4.1.1 Land-use changes in gully catchments

In the above section (4.1), a quantification of land-use change across the entire study area has been presented, but to use this information to understand changes in gully characteristics, it is important to understand how land use has changed in individual gully catchments. Gully catchment were defined using the methods described in section 3.2.2.1.7. A total of 22 catchments were delineated. Some catchments had more than one gully and a possible reason for this condition are explained in section 4.3. The 2014 satellite imagery of the study area (Table 3.4) covers eight of the 22 catchments and land-use changes in these catchments (IdNorthWS, IdSouthWS1, IdeatoSouth_gully1, IdeatoSouth_gully2, IdeatoSouth3, Isu_gully1, Isu_gully2, Isu_gully3) were identified in between 2009 and 2014, and 2014 and 2018. These results provided greater resolution of stepwise changes in land use.

Table 4.4 shows land-use changes in the gully catchments. In two (IdNorthWS, IdSouthWS1) of the eight catchments captured in the 2014 imagery, there was initial rise in non-vegetated lands between 2009 and 2014 and subsequent decline in 2018. Apart from the IdSouthWS1 gully catchment, there was tree/fallow-cover reduction across all catchments between 2009 – 2018 (Table 4.4), this result is similar to those shown in figure 4.3 for the entire study area. With regards to the non-vegetated class, NjabaWS1 and IdSouthWS1 were the only catchments that experienced reductions in land area covered by bare surfaces and built-up areas between 2009 and 2018. In summary, results show that while there could be increase in a land-use class across the entire study area, land use is heterogenous in individual gully catchments. This variation in land-use potentially affects changes in gully characteristics.

Table 4.4: Land-use changes in the 22 gully catchments. Apart from IdSouthWS1, there is tree/fallow-cover reduction across all catchments.

No.	Catchment name		2009			2014			2018		
		Catchment area (km^2)	Non-veg (%)	Open veg (%)	Tree/Fallow (%)	Non-veg (%)	Open veg (%)	Tree/Fallow (%)	Non-veg (%)	Open veg (%)	Tree/Fallow (%)
1	IdNorthWS	0.53	16.84	35.99	47.16	25.71	51.6	22.7	17.02	70.92	12.06
2	IdSouthWS1	0.08	19.51	71.95	8.54	37.8	34.15	28.05	2.44	60.98	36.59
3	NjabaWS1	0.13	12.03	66.17	21.8				9.02	89.47	1.5
4	Amucha	10.23	17.58	39.27	43.15				53.09	46.85	0.06
5	IdeatoNorth	5.01	17.69	47.69	34.62				32.49	65.28	2.23
6	IdeatoNorth1	0.35	10.87	39.40	49.73				12.5	71.20	16.3
7	IdeatoSouth_gully1	0.26	25.46	45.39	29.15	57.93	38.01	4.06	59.04	40.96	0
8	IdeatoSouth_gully2	0.31	8.21	54.41	37.39	33.43	50.76	15.81	28.88	70.82	0.3
9	IdeatoSouth3	2.33	18.5	51.38	30.12	48.33	39.59	12.07	49.51	48.62	1.87
10	Isu_gully1	0.14	13.01	41.78	45.21	23.97	63.7	12.33	36.3	63.7	0
11	Isu_gully2	0.07	15.07	60.27	24.66	23.29	68.49	8.22	61.64	38.36	0
12	Isu_gully3	0.06	3.33	40	56.67	8.33	70	21.67	28.33	71.67	0
13	Njaba2	1.28	15.51	46.75	37.74				24.74	71.79	3.47
14	Njaba4	2.78	12.44	48.01	39.55				44.38	55.59	0.03
15	Njaba5	29.31	20.30	38.69	41.00				50.82	48.57	0.61
16	Orlu1	8.34	26.18	56.46	17.36				63.65	36.32	0.03
17	Orlu2	1.71	28.95	55.83	15.23				45.89	54.05	0.06
18	Urualla_gully1	0.85	13.95	59.04	27.01				38.5	59.15	2.34
19	Urualla_gully2	5.38	16.23	46.47	37.3				29.87	66.81	3.32
20	Urualla_gully3	0.79	19.98	59.22	20.81				26.4	71.94	1.66
21	Obibi-Ochasi	0.85	20.04	57.56	22.40				27.32	71.89	0.78
22	Umueshi	0.31	18.77	33.23	48				36.31	61.23	2.46

4.2 Change in gully characteristics between 2009 and 2018

In 2009, a total of 26 gullies covering an area of 0.36 km^2 were identified and mapped (section 3.2.1.2 describes methods used for mapping). This number increased to 39 gullies occupying 0.62 km^2 of land in 2018, thus, there was an increase of 50% and 75% in gully numbers and gullied areas respectively (figure 4.4). Out of all mapped gullies, seven were visited during fieldwork. These seven gullies were found in Urualla, Isu Njaba, Obibi-Ochasi, Amucha and Umueshi. While one gully in Urualla is currently being managed, the Umueshi gully restoration project had been abandoned as at the time of gully visit (May 2019). The drone survey described in section 3.2.1.2 captured two gullies (Urualla_gully1 and Urualla_gully2) as shown in figure 4.5.

In addition to an increase in the number of gullies between 2009 and 2018, gully width, area and length changed (figures 4.6 – 4.8). In 2009, gully length ranged from 0.05 to 1.4 km with a mean of 0.39 and standard deviation of 0.35 (Table 4.5). The total length of all gullies was 10.22 km in 2009.

Table 4.5: Summary statistics of changes for gully dimensions of the 39 gullies mapped in 2018. 26 gullies were identified in 2009.

	2009				2018			
	Mean	Max	Min	SD	Mean	Max	Min	SD
Length (km)	0.39	1.40	0.05	0.35	0.43	2.00	0.05	0.39
Width (m)	34.53	59.24	15.20	9.89	35.26	72.23	10.40	15.82
Area (m^2)	13774.91	47530.11	1438.69	13158.37	16432.21	57678.78	978.00	16632.58

In 2018 however, total gully length was 16.63 km with range values between 0.05 to 2 km, a mean value of 0.43 and standard deviation of 0.39 (Table 4.5). For the 39 gullies identified in 2018, Table 4.5 indicates a mean increase in gully length of 0.04 km in the 10 years of study period or an annual length growth of 4 m yr^{-1}.

Two different calculations were performed for 2018 gully dimensions:

a) Twenty-six gullies that were mapped in the 2009 satellite imagery (older gullies)
b) Thirteen gullies that were identified for the first time in the 2014 or 2018 imagery (newer gullies)

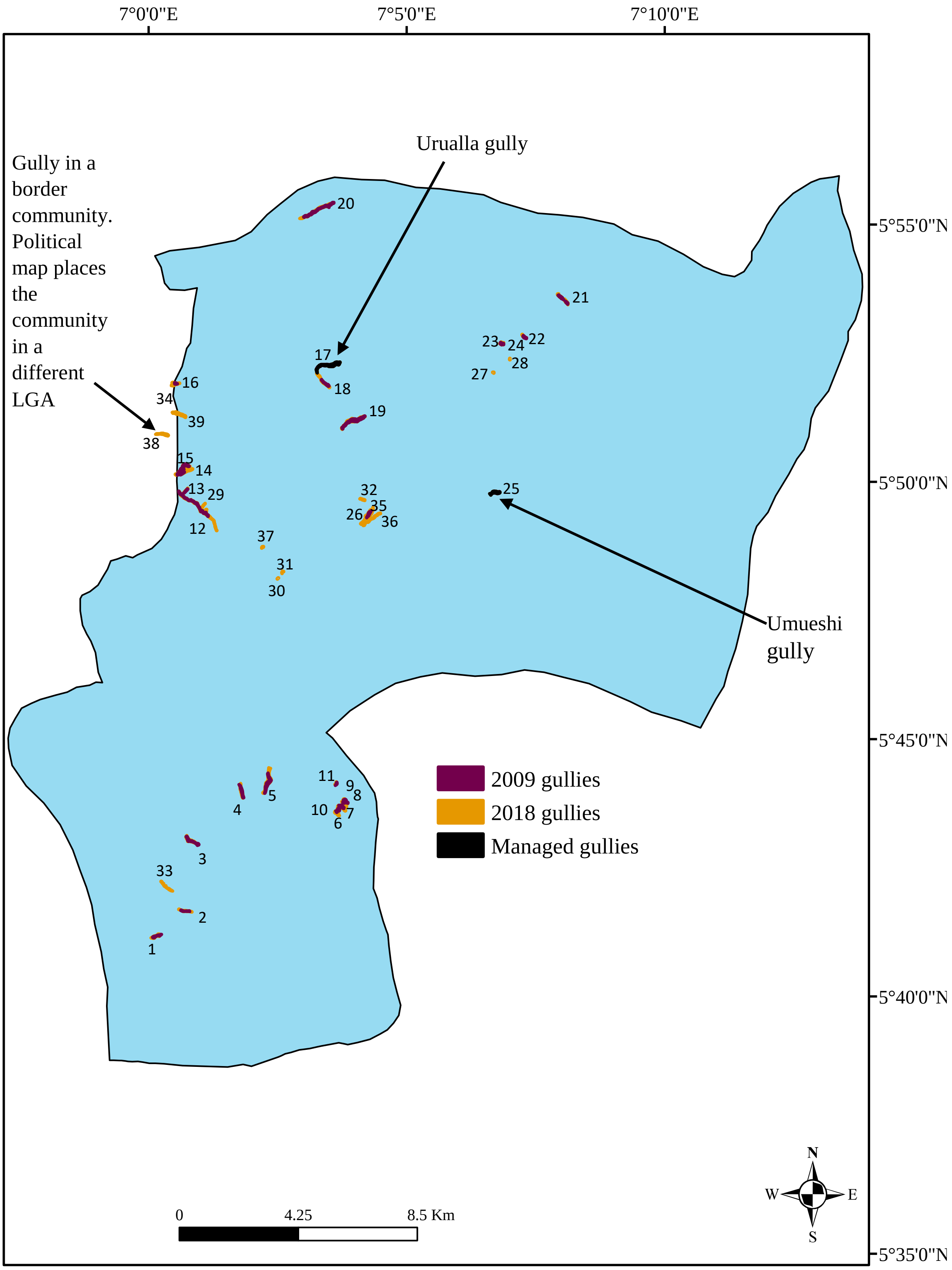


Figure 4.4: Gully map showing gully changes between 2009 and 2018. One identified gully (no. 38) lies on the border between Orlu and Orsu LGAs, the community was not captured appropriately in the political map, however, during fieldwork, the gully was found to be in Orlu LGA. One gully (no. 17) in Urualla community is currently under management while the Umueshi (no. 25) management project had been abandoned at the time of site visit. Gully IDs are shown.

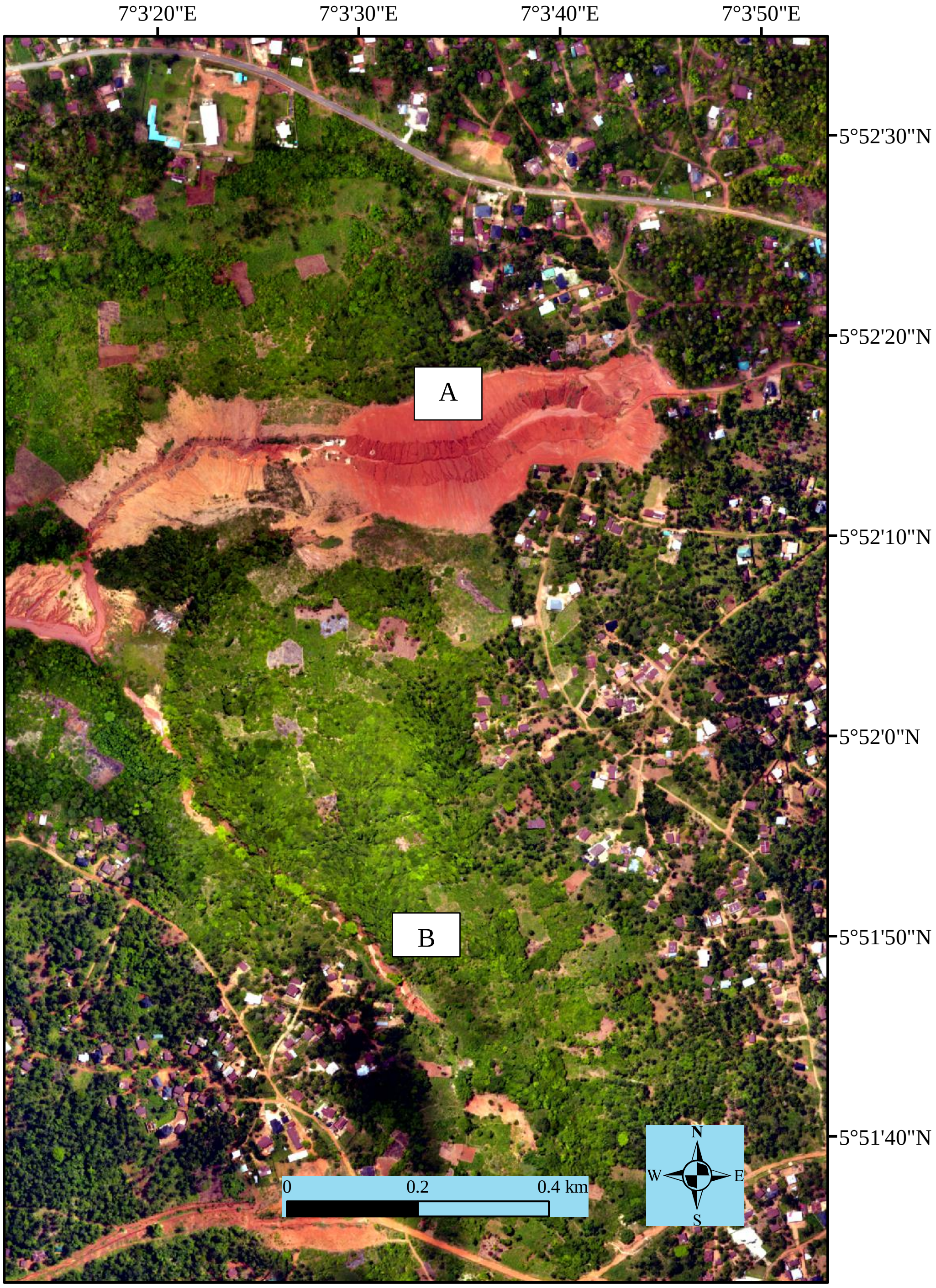


Figure 4.5: Drone image of two gullies in Urualla community captured on 7th May 2019. Gully A (Urualla_gully1) is currently under management, while gully B (Urualla_gully2) is not. Source: Loraj Consortium, May 2019.

The 26 gullies that were identified in 2009 had the following dimensions in 2018: mean length of 0.5 km, average width of 40.72 m and mean gullied area of 21366.8 m^2. Thus, there are mean headward, lateral and areal increase of 11, 0.6 m yr^{-1} and 759.2 m^2 yr^{-1} respectively among the older gullies, conversely, the 13 newer gullies had a mean length of 0.28 km, mean width of 23.79 m and mean gullied area of 7212 m^2. Seven gullies were mapped in the 2014 satellite data. Of these seven gullies, four were present in 2009 and had mean headward, lateral and areal retreat rates of 6.25 m yr^{-1} and 2.1 m yr^{-1}, 0.2 and 0.9 m yr^{-1} and 327.7 m^2 yr^{-1} and 551.5 m^2 yr^{-1} between 2009 – 2014 and 2014 – 2018 accordingly. Three new gullies were recognised in the 2014 satellite data and possessed mean headward, lateral and areal retreat rates of 48.7, 1.7 m yr^{-1} and 1352.6 m^2 yr^{-1} between 2014 and 2018.

Mean gully width for the 39 gullies mapped in 2018 increased from 34.53 m to 35.26 m, while maximum width increased from 59.24 to 72.23 and a change in standard deviation of the width from 9.89 to 15.82 was observed between 2009 and 2018 (Table 4.5). Mean gullied area increased from 13775 to 16432 m^2 indicating an areal retreat of 266 m^2 yr^{-1}. Minimum gullied area reduced from 1439 to 978 m^2 between 2009 and 2018. The minimum value of 978 m^2 belongs to a newly formed gully which was identified in 2018, Total land area under gully occupation in the five LGAs of interest as at 2018 was 0.62 km^2.

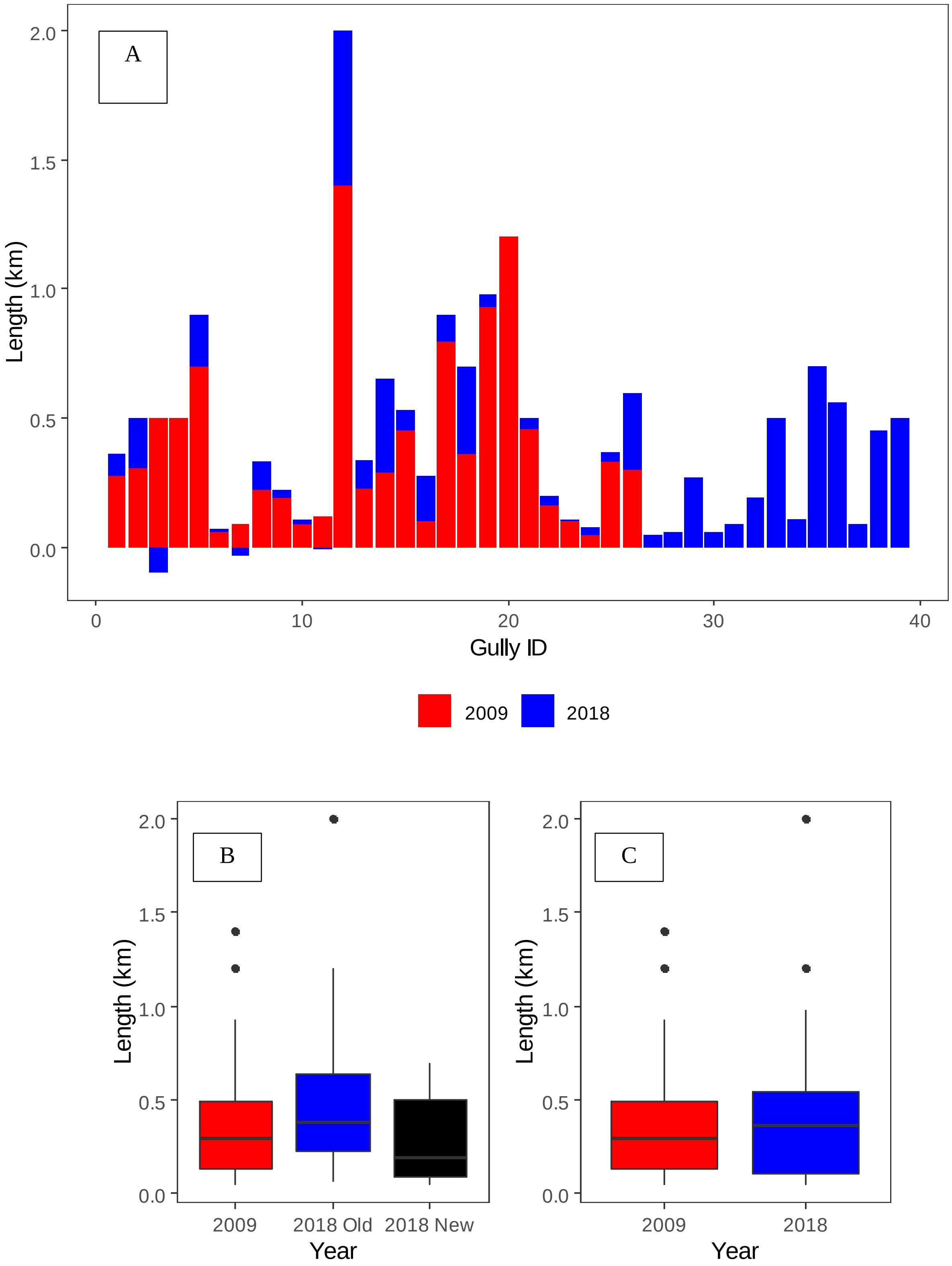


Figure 4.6: Gully length A) stacked bar chart showing gully lengths for 2009 and 2018, B) Boxplot representing changes in length. 2018 old refers to the 26 gullies mapped in 2009 while 2018 New refers to 13 new gullies identified in 2018, C) Boxplot showing change in gully length. Sample size was 26 in 2009 and 39 in 2018.

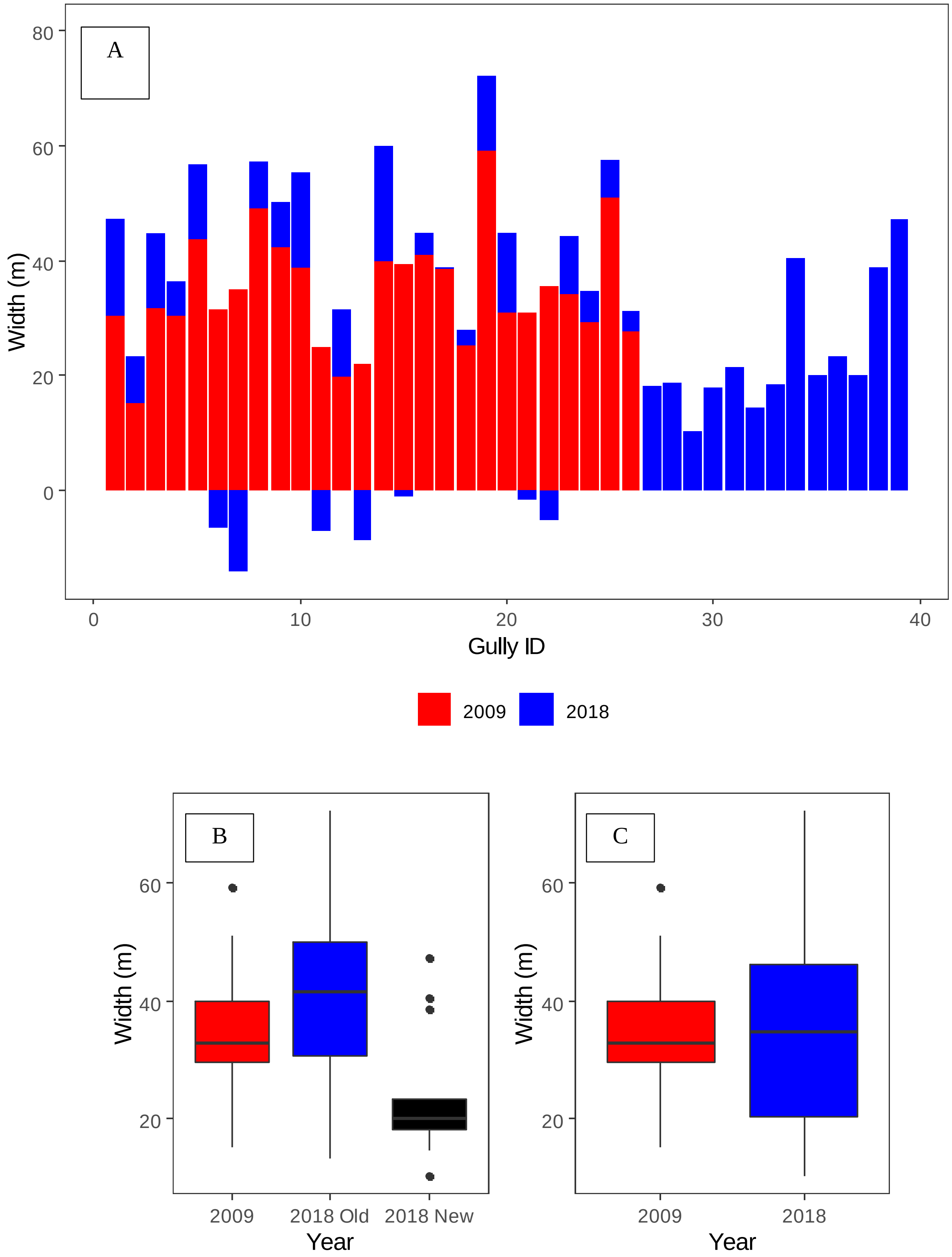


Figure 4.7: Gully width A) Stacked bars show gully widths in 2009 and 2018. B) Boxplot representing changes in width. 2018 old refers to the 26 gullies mapped in 2009 while 2018 New refers to 13 new gullies identified in 2018. C) Boxplot representing change in average gully width. Sample size was 26 in 2009 and 39 in 2018.

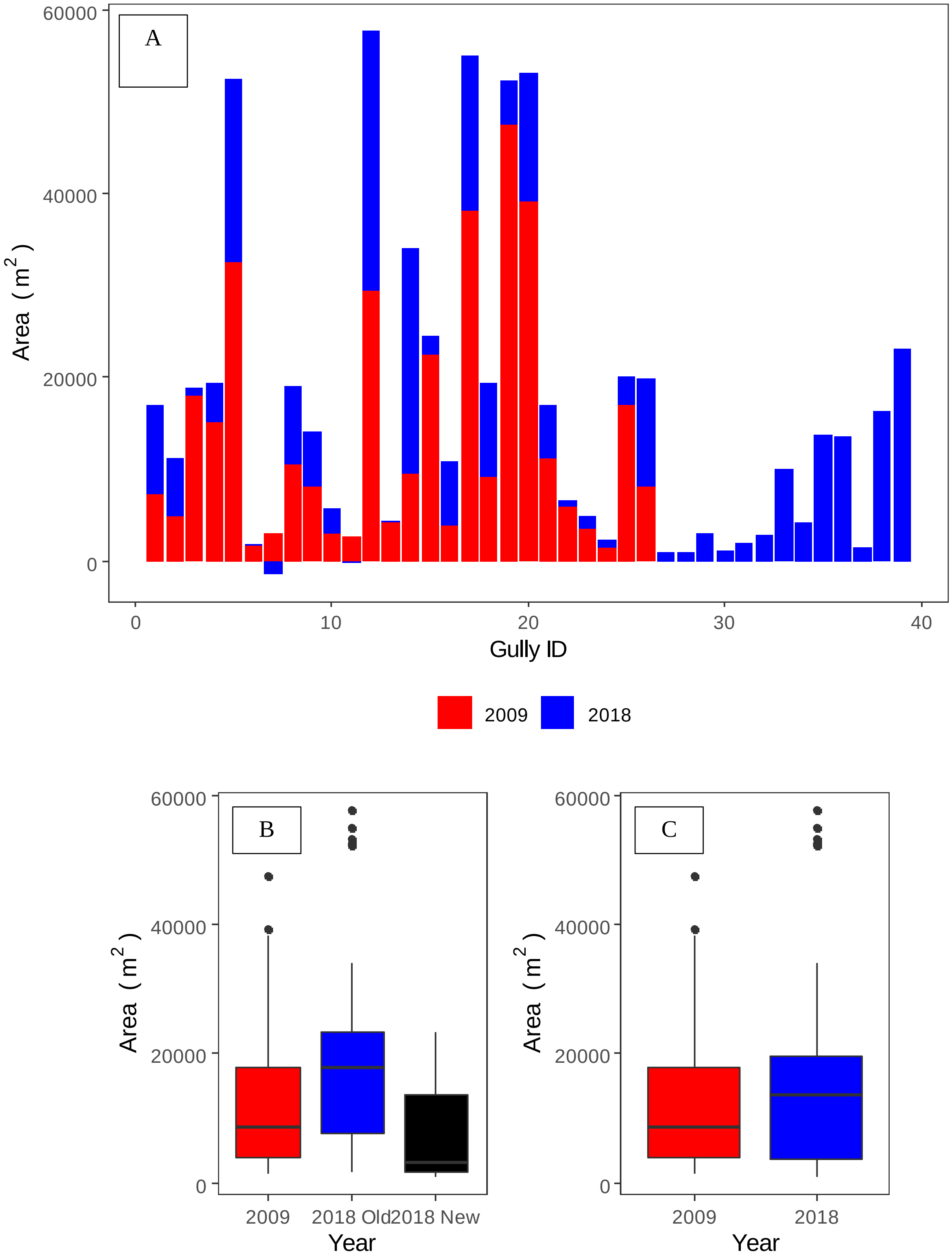


Figure 4.8: Gullied area. A) Stacked bars represent 2009 and 2018 gullied areas. B) Boxplot representing changes in area. 2018 old refers to the 26 gullies mapped in 2009 while 2018 New refers to 13 new gullies identified in 2018, C) Boxplot showing change in gullied area between 2009 and 2018. Sample size was 26 in 2009 and 39 in 2018.

4.3 Changes in gully characteristics with respect to land use and land-use changes

Gully changes across the 22 delineated catchments are presented in Table 4.6 and Appendices 4.1 and 4.2. Some catchments, e.g. Orlu1 and Orlu2 have more than one gully. The following reasons are provided for the occurrence of more than one gully in a catchment, first, the resolutions of satellite imagery and the DEM. Satellite data used for gully mapping had resolutions between 0.61 – 5 m while the drone survey data had a resolution of 0.4 m. However, a 30 m DEM was used to delineate watersheds. Secondly, closeness of gullies. Gullies were found close to each other in all catchments where more than one gully was mapped (gullies 14 and 15 belong to the Orlu2 catchment and are <10 m apart in some places, figure 4.9). Considering the 30 m resolution of the DEM and gully distance of <10 m from one another, the DEM may not likely delineate two different catchments for both gullies. Also, extensive vegetal cover can make a single gully appear in two different parts, and thus when mapping such gullies from satellite imagery, more than one gully is identified, whereas, the gully was a single continuous gully which had been separated into different units by vegetation. Finally, tributary gullies (referred to by the local communities as gully-fingers); a gully might flow directly into another gully and during mapping, more than one gully is identified but the same catchment feeds both gullies (examples were found in Orlu 1 catchment where smaller gullies emptied into the central gully with a length of 2 km) (figure 4.9). Albeit, while single catchments were defined for close and tributary gullies, individual sub-basins were delineated for different gullies within same catchment.

Land can be used in a variety of ways which can affect gully erosion (e.g. gully rehabilitation, changes in land use from tree/fallowed lands to non-vegetated surfaces, and road construction). Regarding gully rehabilitation, the Urualla_gully1 (Table 4.6 and figure 4.5) was under management during site visit. As part of the management, excavators and other heavy equipment have been used to compact the soils around the gully so trucks can deliver laterite (needed for infilling) to the gully without sinking. This increased compaction may possibly reduce infiltration, thereby increasing surface runoff (Yibeltal et al. 2019) which eventually ends up in the gullies. In relation to land-use changes, there was an increase in non-vegetated areas at the Urualla_gully1 Catchment for the study period (Table 4.4) while the gully experienced a 0.2 m increase in width (Table 4.6). Although a 0.2 m lateral growth was recorded at for this gully, interview with the contractors during fieldwork suggests that the width of this gully had reduced due to in-filling with laterite, thus, it is possible width expansion is more than the 0.2 m documented. Although there is a 100 m increase in gully length between 2009 and 2018 (Table 4.6), considering gully in-filling, it is possible actual gully length growth is >100 m for Urualla_gully1.

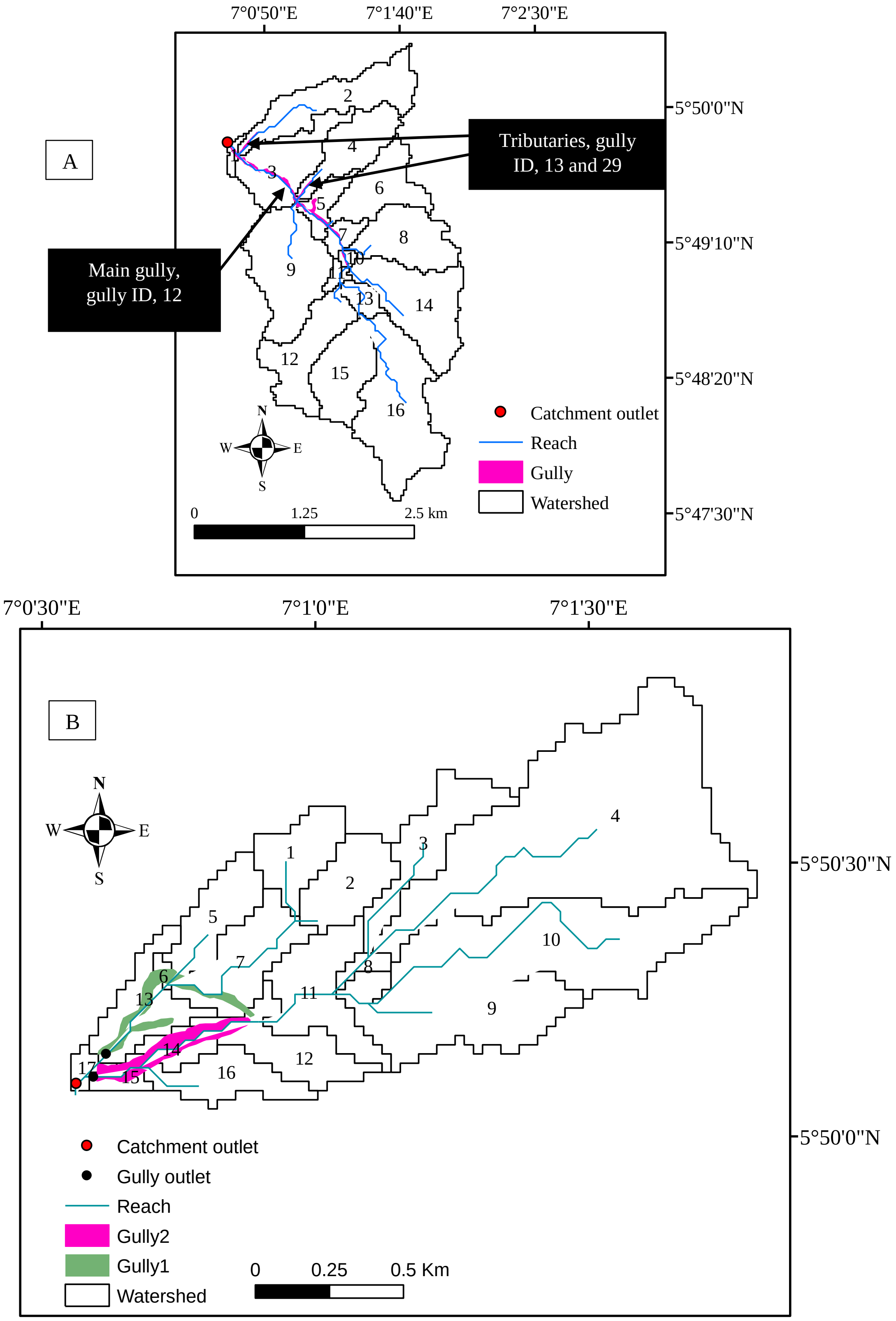


Figure 4.9: A, Orlu1 catchment showing main gully (ID, 12) which is 2 km long and tributary gullies (13, 29). While a single catchment was defined for main and tributary gullies, individual sub-basins were delineated for different tributary gullies. B, Orlu2 gully watershed (ID, 14 and 15) showing closeness of both gullies which is < 10 m in some points.

Two catchments (IdSouthWS1 and Njaba WS1) experienced reductions in non-vegetated areas. While there was an increase in the gully length in IdSouthWS1 between 2009 and 2018, no longitudinal gully extension was observed in NjabaWS1 between 2009 and 2018 (Appendices 4.1 and 4.2). The gully width in NjabaWS1 increased by 6.1 m between 2009 and 2018 whereas there is a sustained reduction in mean gully width in the IdSouthWS1 catchment from 35.67 m in 2009 to 32.14 m in 2014 and to 30.53 m in 2018 (Table 4.6). Table 4.4 shows a rise in tree/fallow cover in IdSouthWS1 for same period, thus it is possible the increased fallow masked the actual width of the gully. It is also possible that the gully in IdSouthWS1 catchment is beginning to stabilise due to higher vegetal cover which could trap and retain transported sediments (Dong et al. 2013; Rey et al. 2019) and thereby increasing the possibility of lateral gully-infilling from deposited materials. Although there was a reduction in non-vegetated areas in NjabaWS1, fallow/tree-cover reduced while there was increase in open-vegetated areas (Table 4.4) which corresponded to increase in gully width. Thus, no clear pattern is established between reductions in non-vegetated areas and changes in gully features (e.g. length or width) in these two catchments. This finding points to the uniqueness of individual catchments and gully responses to other drivers of gully expansion other than land-use changes.

Isu_gully1, IdeatoNorth1 and Orlu2 experienced gully-width reductions while there was an apparent 100 m reduction in gully length in Njaba2 between 2009 and 2018 (Appendices 4.1 and 4.2). Table 4.4 shows reductions in fallow cover in these catchments, yet reductions in gully dimensions were observed. It is possible that while the entire catchment experienced reduced fallow cover, the areas surrounding the gullies were vegetated at the time of satellite data capture, as observed in Njaba2. Hence, the higher vegetated cover around the gullies possibly hid the actual gully dimensions. It also possible that gullies in these catchments are beginning to stabilise and fill-up (Rey et al. 2019).

The gully in IdeatoSouth_gully1 catchment was mapped in 2009 but seemed to have been filled in 2014 as the gully surface was covered in the 2014 satellite data. In 2014, a new gully (IdeatoSouth_gully2) was identified and by 2018, the new gully had grown to 0.56 km. The IdeatoSouth_gully1 reappeared in 2018 and had attained a length of 0.6 km. Gully width and area also increased for these two gullies. These changes in gully dimensions corresponded to sustained reduction in fallow-cover and higher non-vegetated areas in both catchments (Table 4.4). All other catchments, e.g. Amucha, Orlu1, Orlu2 experienced increases in gully sizes

(Appendix 4.2) corresponding to reductions in fallow/tree cover and increase in non-vegetated surfaces (Table 4.4).

Table 4.6: Changes in gully characteristics between 2019 and 2018. Gullies not covered by the 2014 satellite imagery have empty cells.

number	Catchment id	Gully length 2009 (km)	Average width 2009 (m)	Area 2009 (m^2)	Gully length 2014 (km)	Average width 2014 (m)	Area 2014 (m^2)	Gully length 2018 (km)	Average width 2018 (m)	Area 2018 (m^2)
1	IdNorthWS	0.10	34.09	3556.51	0.10	38.07	3954.04	0.11	44.17	4901.54
2	IdSouthWS1	0.16	35.67	5879.47	0.20	32.14	6935.23	0.20	30.53	6588.71
3	NjabaWS1	0.50	30.31	15166.21	-	-	-	0.50	36.42	19370.75
4	Amucha	0.70	43.63	32507.58	-	-	-	0.90	56.68	52462.40
5	IdeatoNorth	1.20	31.00	39182.56	-	-	-	1.20	44.84	53182.36
6	IdeatoNorth1	0.46	30.85	11269.59	-	-	-	0.50	29.11	16928.81
7	IdeatoSouth_gully1	0.3	27.81	8125.21	0	0	0	0.6	31.07	19892.18
8	IdeatoSouth_gully2	0	0	0	0.36	12.3	5060.38	0.56	23.4	13532.57
9	IdeatoSouth3	0.00	0.00	0.00	0.1	10.90	1101.59	0.19	14.51	2849.90
10	Isu_gully1	0.22	49.00	10622.14	0.32	45.00	14835.26	0.33	57.3	21497.26
11	Isu_gully2	0.19	42.30	8203.21	0.2	50.14	10402.20	0.22	55.0	14170.15
12	Isu_gully3	0.06	31.4	1723.3	0.06	31.4	1723.3	0.23	50	11661.1
13	Njaba2	0.50	31.80	18027.20	-	-	-	0.40	44.89	18803.96
14	Njaba4	0.30	15.23	4864.72	-	-	-	0.50	23.29	11286.57
15	Njaba5	0.00	0.00	0.00	-	-	-	0.50	18.37	10008.44
16	Orlu1	1.40	19.76	29442.05	-	-	-	2.00	31.46	57678.78
17	Orlu2	0.45	39.22	22488.93	-	-	-	0.53	38.25	24480.47
17	Orlu2	0.29	40.00	9556.86	-	-	-	0.65	60.00	34104.62
18	Urualla_gully1	0.8	38.66	38163.6	-	-	-	0.9	38.86	52081.21
19	Urualla_gully2	0.36	25.37	9235.18	-	-	-	0.70	27.87	16236.45
20	Urualla_gully3	0.93	59.24	47530.11	-	-	-	0.98	72.23	52235.44
21	Orlu3	0.00	0.00	0.00	-	-	-	0.50	50.69	23192.34
22	Umueshi	0.33	51.1	17030.52	-	-	-	0.37	57.6	20059.74

To quantify the association between changes in land use and responses from gully dimensions, multiple regression analyses were performed on two sets of data, first, gullies captured in the 2009 to 2018 imagery and secondly, on gullies captured in the 2014 satellite data. There is a positive correlation between changes in non-vegetated and open vegetation classes ($r^2 = 0.35$, $p = 0.03$), whereas, a negative association exists for non-vegetated classes and tree/fallow ($r^2 = 0.94$, $p < 0.05$), and open vegetation and tree/fallow class ($r^2= 0.6$, $p < 0.05$). Based on these initial analyses, two land-use classes, non-vegetated and tree/fallow were selected as predictive variables while gully length, width, and area were the outcome variables, detailed results are shown in Appendices 4.3 – 4.11. For the 2009 – 2018 datasets, only the associations between gully length, non-vegetated and tree/fallow class were significant at 95% confidence level (p-value = 0.04, adjusted $r^2 = 0.33$). For the years 2009 – 2014 and 2014 – 2018, no significant associations were found between predictive and outcome variables at 95% confidence level (Appendices 4.6 – 4.11). The reason for the insignificant associations between gully dimensions and changes in land use between 2009 and 2014 and 2014 and 2018 could be due to the shorter-term nature of these study periods in comparison with the 10 years of land use changes between 2009 and 2018.

Lands are used for road construction which often involves tarmac surfaces. These tarmac surfaces discourage infiltration and produce surface runoff which could in turn facilitate gully erosion. Figure 4.10A shows compacted surface at the Urualla gully site while figure 4.10B shows a tarmac road network map of the study area. One example of land-use change is road construction, which often involves entire conversion of lands from forest or farms to asphalt surfaces. Figure 4.11 shows gully endpoint and gully head proximity to roads respectively. These results suggest that gully endpoints are farther from the roads than gully-heads (figure 4.11). Average gully endpoint distance from road is 382.24 m while average gully-head distance from road is 142.74 m. There are inverse associations (see figure 4.17 in section 4.4.1) between gully-head distance from road and changes in gully dimensions.

These results on gully head and end point distance from roads show potential driving mechanism of gully-head expansion. The effect of concentrated surface runoff flowing out of main roads will be felt more at gully heads closer to roads, thus, these gullies will have higher growth/expansion rates than gullies farther from main roads, and this mechanism of reduced erosive power of surface runoff with increased distance from main roads explains the negative association between gully-head distance from roads and changes in gully characteristics see (figure 4.17 in section 4.4.1). Another factor worthy of consideration is the termination of water drains at nearby bushes/lands instead of at a local base level. This condition which leads to accelerated erosion due to the concentrated nature of runoff flowing in a drainage channel is often found next to main roads in the study area. Finally, abandonment of road construction or gully rehabilitation projects also facilitates gully expansion. Some examples were found in Umueshi and Obibi-Ochasi Communities where due to abandoned engineering projects, constructed drainage channels which were supposed to carry surface runoff to local base levels were left midway. Thus, concentrated volume of runoff from these abandoned projects is likely to have ended up in the gullies, thereby increasing gully expansion. Figures 4.12 show proximity of gully heads to main roads.

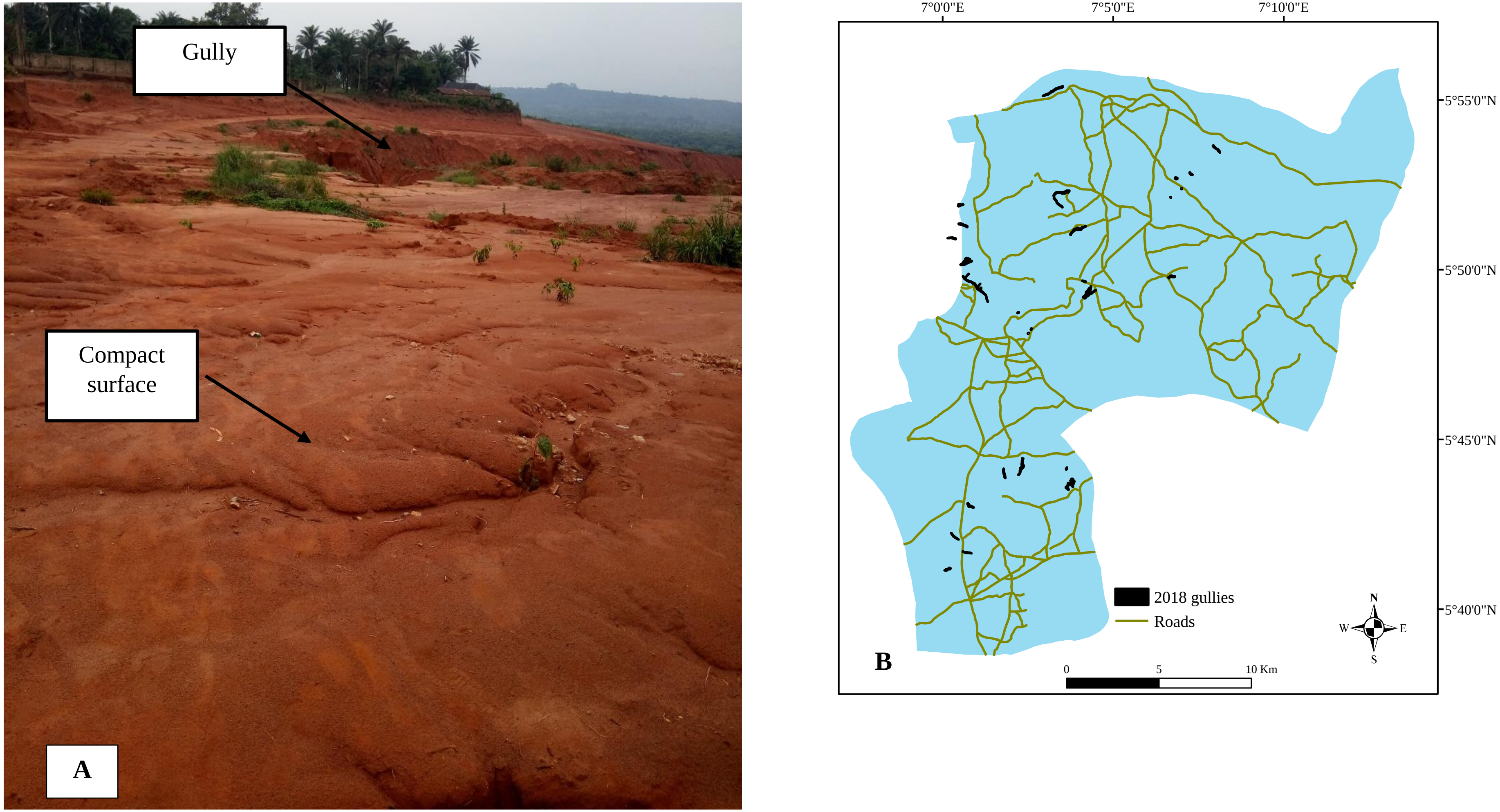
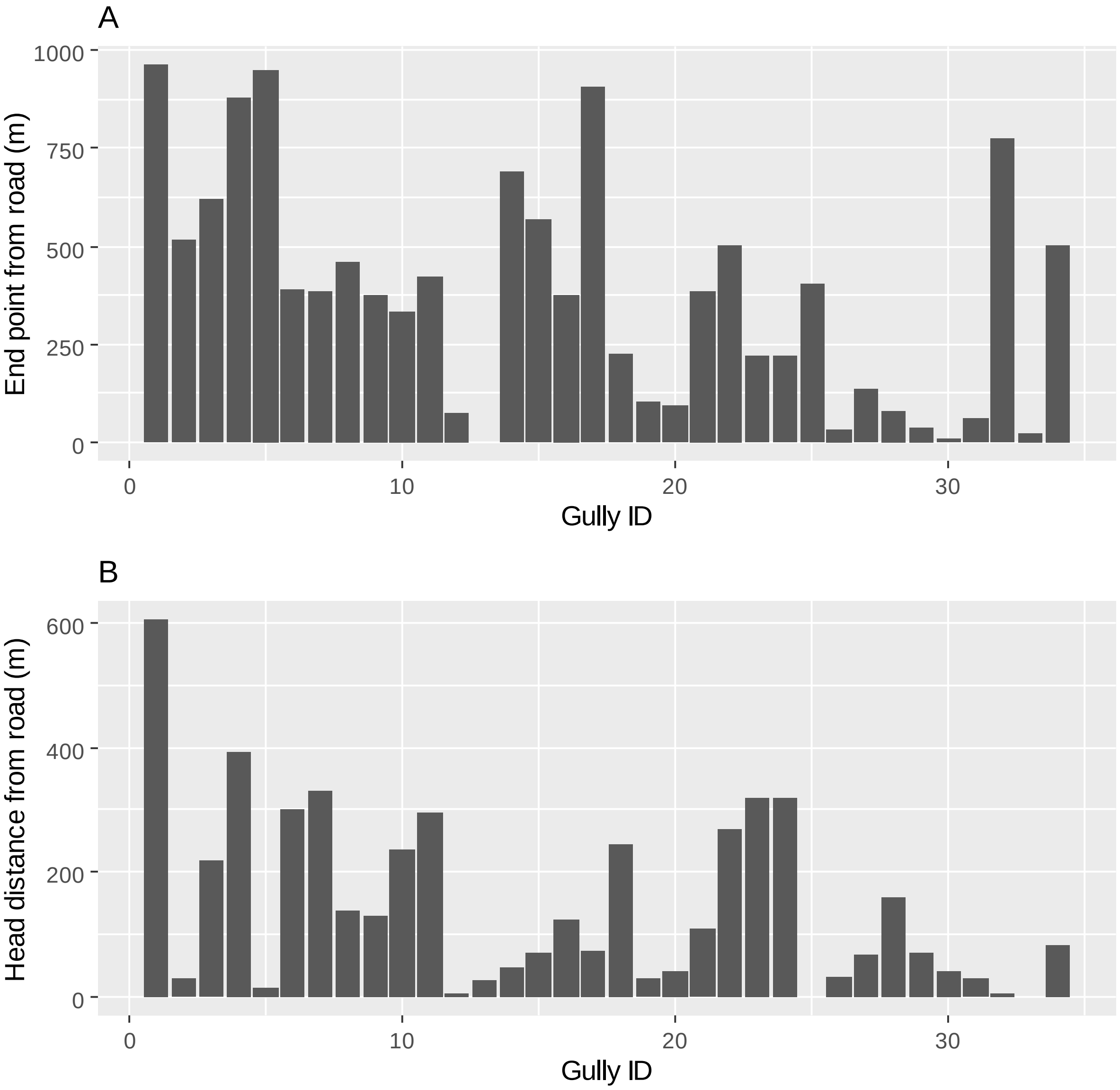


Figure 4.10: Compacted surface close to the gully at Urualla Community, B, Road network map of study area. These roads have tarmac surfaces.



4.11: A. Gully endpoint distance from road, B) Gully-head distance from road. Gully-heads are closer to the roads while endpoints are farther from roads. Mean gully endpoint distance from road is 382.24 m while mean gully-head distance from road is 142.74 m.

Figure 4.12: Proximity of gully heads to main roads. A, shows a moving truck close to a gully in Okwudor, Njaba LGA. In the first month of fieldwork (April 2019), gully A was not visible on the road, but in June when the picture was taken, it had grown to where it was on the picture. B) shows drainage structure which empties into a newly formed gully in Obibi-Ochasi, Orlu LGA. Road construction was abandoned at this site and according to focus group meeting respondents, B started in 2017 and had grown by 492 m during field visit in 2019. C) shows gully head advancement following abandoned gully restoration project in Umueshi Community. The gully now destroyed the local road connecting two communities. Also visible in C are destroyed drainage channel which delivers runoff directly into the gully and concrete structure designed to control gully erosion.

From the foregoing, it has been shown that between 2009 and 2018, there were changes in land use across the entire study area as shown in figure 4.3 as well as within the delineated gully catchments (Table 4.4). In same period, there was an increase in not just gully numbers, but also other gully dimensions (figures 4.6 – 4.8). Fieldwork observations showed that gully management practices could alter gully dimensions, thus, reducing actual growth of gullies as visible from satellite imageries. Also, where gully rehabilitation projects are abandoned, there could be accelerated gully expansion (Figure 4.12). Actual gully sizes might be covered by vegetation growing inside and around the edges of a gully (figure 4.13) thereby apparently reducing sizes of mapped gullies. While it is important to understand the influence of land use and land-use changes on gully characteristics, the conceptual model presented in Chapter 2 indicates there are other factors whose interactions with land use affect gullying and these factors are discussed in section 4.4.

Figure 4.13: Vegetal cover (which could conceal actual gully dimensions) growing inside and around gully edges.

4.4 What other factors drive changes in gully characteristics?

Previous studies identified the roles played by certain factors as agents of gully evolution and they include physical factors such as slope angle, topography, curvature, proximity to rivers, soil properties, and human elements, for example effects of civil unrest (Ofomata, 1987; Obi & Salako, 1995; Nwilo et al. 2011; Gómez-Gutiérrez et al. 2015; Rahmati et al. 2017; Poesen, 2018). Results on these factors will be provided in the following sections.

4.4.1 Physical factors

4.4.1.1 Topographic elements

Influence the erosive power of the flow of surface runoff and surface runoff is the primary driver of gully erosion (Zevenbergen & Thorne 1987; Poesen et al. 2003; Knapen & Poesen, 2010; Gómez-Gutiérrez et al. 2015). Elevation values in the study area range between 16 and 339 m above sea level thus indicating that the study area is relatively low lying, while the slope varies between 0 – 70% (Figure 4.14). Relative relief and maximum slope values of the 39 gully heads are presented in figures 4.15 and 4.16 with ranges of 6 – 46 m for relative relief, and 12 and 58.2 % rise in slope. Results from these two geomorphic variables indicate that gully heads with the highest relative relief and maximum slope values do not necessarily have the highest rate on change in gully characteristics (figures 4.15 and 4.16) and thus, the effects of these geomorphic variables (as a stand-alone) measured at the gully heads on gully dimensions are not very clear in this study area. Figure 4.17 presents a correlation matrix of gully dimensions and driving factors.

To explore the relative importance of driving factors on changes in gully sizes, Principal Component Analysis was performed. Eigen vectors for the variables of interest show that along the first component, geomorphic factors have the same contribution while gully head distance from river and gully head distance from roads contribute towards the second component (Table 4.7). 46% of variance in the data is explained by principal component 1 while both principal components 1 and 2 explain 82% of variance (Table 4.8). Having identified the importance of the variables of interest, one geomorphic factor (relative relief), gully head distance from road and gully head distance from rivers were chosen as input for multiple regression (Tables 4.9 – 4.11). Of the three gully driving factors considered in the multiple regression, only gully head distance from rivers had a significant positive effect on change in gullied area (Table 4.9).

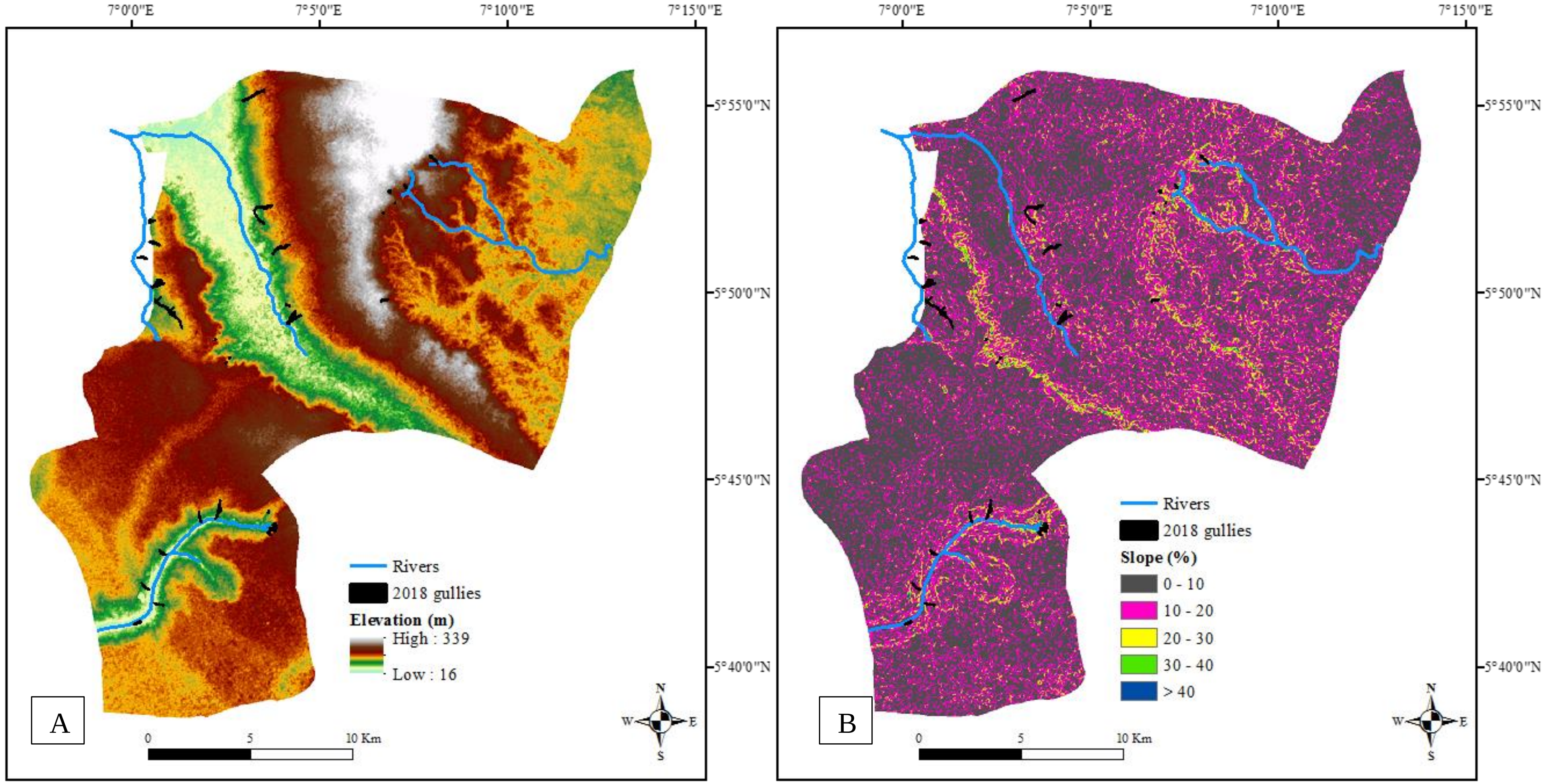


Figure 4.14: A, Elevation map of study area. Also shown are the rivers in the area. These rivers occupy the lowest elevation but surrounding lands have the highest gully concentration. B) Slope map. Land areas around the rivers have higher slope rises (10 – 58.2% rise in slope within distances less than 500 m from the river).

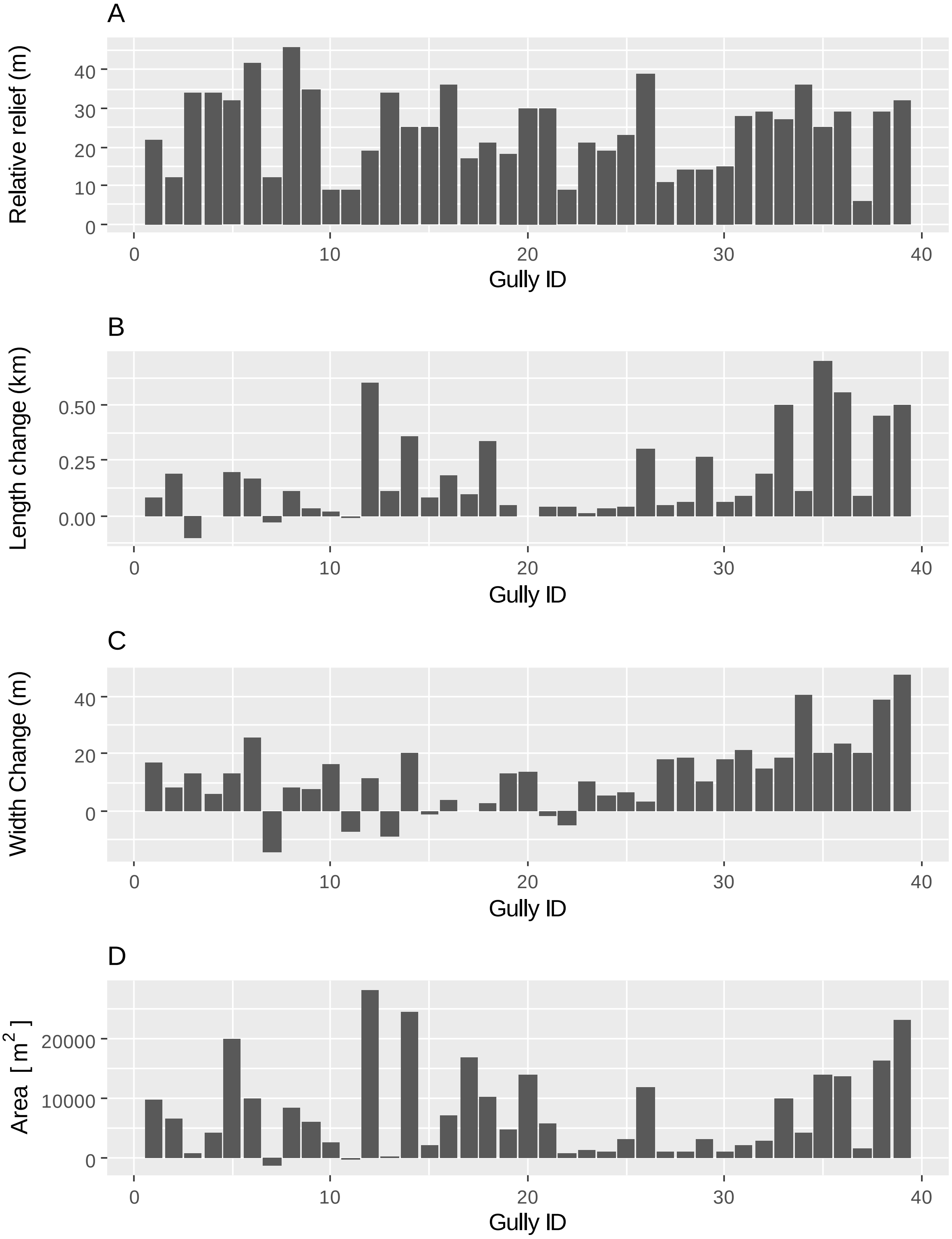


Figure 4.15: A) Relative relief values of 39 gully heads, B) change in gully length, C) change in gully width, D) change in gullied area from 2009 to 2018.

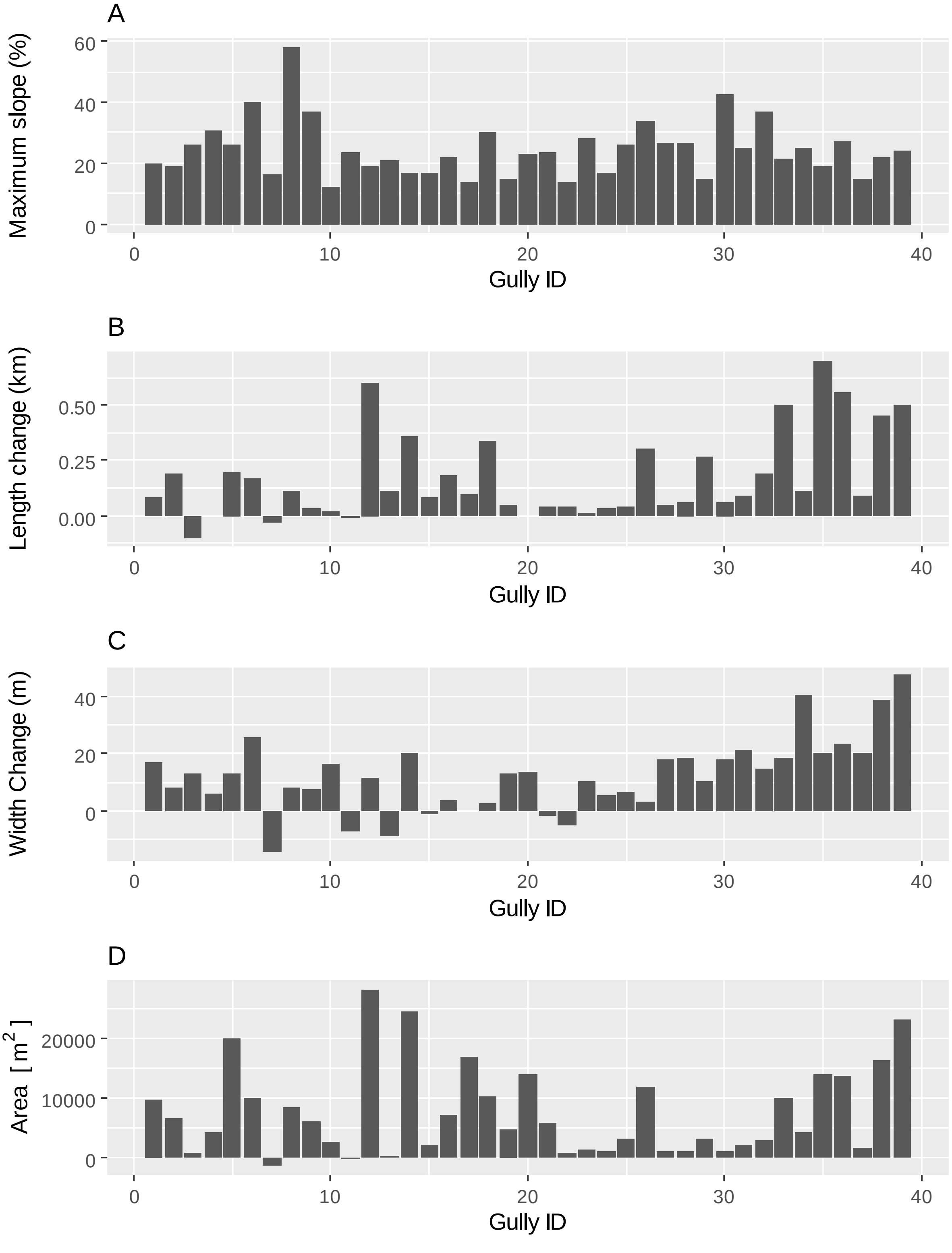


Figure 4.16: A) Maximum slope of gully heads, B) change in gully length, C) change in gully width, D) change in gullied area from 2009 to 2018.

Figure 4.17: Correlation matrix for gully drivers. Effects of maximum slope and relative relief of gully head on changes in gully dimensions are small. GHDri = Gully head distance from rivers, GHDrd = Gully head distance from roads, Corr = Correlation legend.

Table 4.7: Eigen vectors/loadings of variables of interest. GHDri = Gully head distance from rivers, GHDrd = Gully head distance from roads

Variable	Component 1	Component 2
Relative relief	0.69	0.16
Maximum slope	0.69	0
GHDri	-0.23	0.67
GHDrd	0	-0.73

Table 4.8: Importance of components

Variable	Component 1	Component 2
Standard deviation	1.35	1.20
Proportion of Variance	0.46	0.36
Cumulative Proportion	0.46	0.82

Table 4.9: Multiple regression results for gullied area, P-value = 0.03, r^2 = 0.3, adjusted r^2 = 0.21

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1597.97	5689.57	0.28	0.78
Relative_relief	128.20	141.81	0.90	0.37
GHDri	8.33	3.42	2.44	0.02
GHDrd	-6.40	10.76	-0.59	0.56

Table 4.10: Multiple regression results for gully length, P-value = 0.1, r^2 = 0.46, adjusted r^2 = 0.22

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	0.10	0.16	0.64	0.53
Relative_relief	0.00	0.00	0.42	0.68
GHDri	0.00	0.00	1.61	0.12
GHDrd	0.00	0.00	-1.02	0.32

Table 4.11: Multiple regression results for gully width, P-value = 0.49, r^2 = 0.3, adjusted r^2 = 0.1

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.96	11.58	0.17	0.87
Relative_relief	0.39	0.29	1.35	0.19
GHDri	0.00	0.01	0.19	0.85
GHDrd	-0.01	0.02	-0.38	0.70

Plan and profile curvatures indicate the effect of the local terrain on overland flow distribution and by extension, gully erosion (Shary et al. 2002: Zabihi et al. 2018). Three classes of both plan and profile curvature were identified; negative, zero, and positive curvatures corresponding to concave, flat, and convex surfaces, respectively. Concave surfaces encourage accumulation of surface flow while convex surfaces support acceleration of flow. There is higher concentration of gullies on convex curvature (Table 4.12), thus, there are higher gully counts on the portions of the slopes where flow acceleration is observed in contrast to where flow accumulation dominates.

Table 4.12: Curvature and gullied area showing high gully count on convex curvatures

Curvature	Gully pixel count
Plan	
Concave	33
Flat	0
Convex	753
Profile	
Concave	11
Flat	0
Convex	775

4.4.1.2 Nearness to rivers

The study area is relatively low-lying (16 – 339 m above sea level), the rivers occupy the lowest portions of the lands (figure 4.14A), yet, the surrounding lands around these rivers have higher slopes and highest gully concentrations. Slopes around the rivers rise from 10 to more than 50% over distances less than 500 m from the rivers (Figure 4.14B), and this situation will lead to surface flow acceleration, especially, as these surface flows drain into the rivers. In addition to the influence of local slope of adjoining lands around the rivers on surface runoff acceleration and subsequently, on gullies, deposited materials in rivers will be transported away (as was observed during fieldwork), thus, creating the space for more deposition from upstream of a gully. This condition leads to a positive feedback between the gully and the river. If these eroded materials were not transported out of the gully channel, they could form protective shields against further erosion, especially, at the gully wall bottoms.

To have a better appreciation of the influence of rivers on changes of gully characteristics, distance measurements were made from the gully endpoint (gully-mouth) to the river, and from the gully head to the river. Gully endpoints are closer to the rivers than gully heads as the average gully endpoint distance from river is 142.4 m while average gully head distance from river is 607.36 m (Figure 4.18). As the slope of the land rises from the river upwards around the surrounding lands, the effect of surface runoff on the gully-head likely increases, thus, there is headward migration upslope and away from the river, this mechanism is the reason for the positive correlation of 0.41 between gully-head distance from river and change in gully length and area (figure 4.17) as well as the significant positive effect of gully-head distance from river and change in gullied area (Table 4.9).

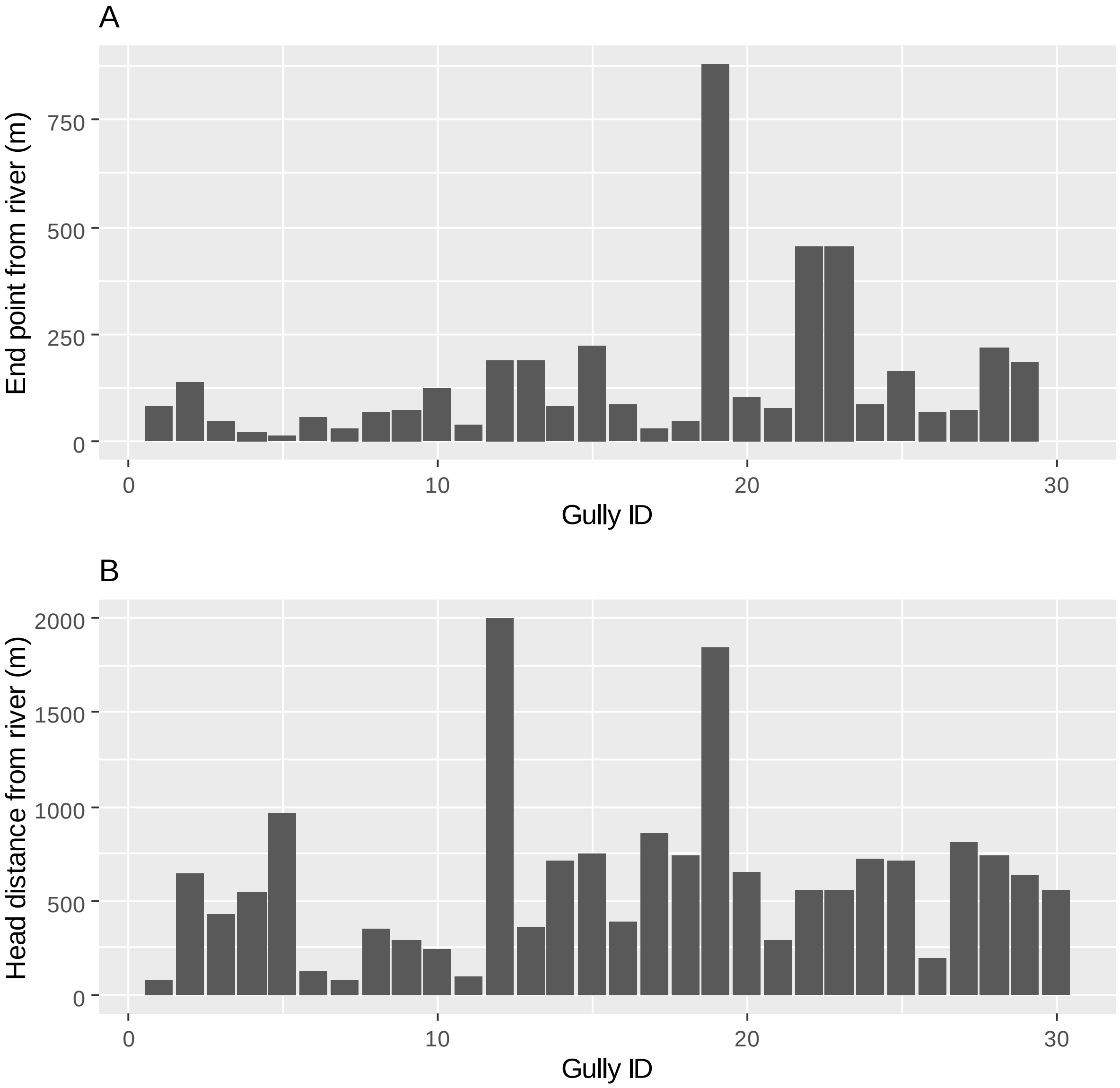


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Figure 4.18: A) Gully endpoint distance from river, B) Gully-head distance from river. The endpoints are closer to the river, while the gully-heads are farther from the rivers. Gully-heads are closer to roads while endpoints are farther from roads (figure 4.10).

4.4.1.3 Soil properties

Soil texture, density and strength (cohesion, shear strength, angle of internal friction) infiltration capacities and moisture contents (section 3.2.1.3). Soil texture is important, especially, as it relates to infiltration capacities of soils (which are significant with regards to production of surface or sub-surface flow) and dispersal. For example, sandy soils are known to have higher infiltration capacities and are said to be more prone to dispersal than soils that are rich in clay and silt (Brown, 1962; Okagbue & Ezechi, 1988). Therefore, mechanism driving gully erosion and gully widening could be different in areas with sandy soils from areas covered by clay soils. Dry density of soils is an important parameter as it influences their reactions to stress while cohesion is the force that binds particles together. Shear strength is an indication of the magnitude of shear stress a soil can withstand while angle of internal friction measures the ability of a soil unit to withstand shearing stress. Infiltration capacities of soils are important for a better understanding of hydrological drivers of gully expansion in response to land-use changes. For example, in a gully catchment covered by trees/fallow, if the soils have high infiltration capacity, production of runoff may be minimal, thus, sub-surface flow could become the primary driver of gullying. If the infiltration capacities of the soils are low, and the land use is predominantly bare, then surface runoff could be the driver of gullying in the catchment.

Soil particle size distribution is shown in Table 4.13. The soils have a higher sand content than silt and clay for all test sites, this condition can predispose the soils to easy dispersal by erosive forces (Okagbue & Ezechi, 1988). Strength test results are presented in Table 4.14, the soils have low cohesion values and this factor may well be due to the higher sand contents of the soils (figure 4.19). The density results (Table 4.14) of the soils are above average for all the sites. Yu et al. (1993) suggested that mean dry density value for sandy soils is 1.52 mg/m^3. The angle of internal friction and shear strengths of the soils are reasonable for sandy soils, however, due to the lower cohesion values and higher loose nature of the soils, effects of the angle of internal friction and shear strengths in resisting shearing forces possibly will be subdued.

Results of infiltration and soil moisture tests are shown in Table 4.15. Boxplots of infiltration rates for different land-use types are presented in figure 4.20. Mean infiltration rates for Isu Njaba are smallest in the study area (20.34 mm/hr for open vegetation and 7.71 mm/hr for fallow), on the other hand, the mean soil moisture content for same site was highest (12% for open vegetation and 19% for fallow). It is possible that due to this higher soil moisture content, there is reduction in infiltration rates at the study sites in Isu Njaba. The lower infiltration rate at the fallow land-use class suggests that with regards to surface runoff, this land-use class will likely produce runoff (infiltration and saturation excess) faster than areas with higher infiltration rates and lower soil moisture content. Bare soils (examples of non-vegetated land use class) at Amucha had the highest infiltration rates for the entire study region with a mean rate of 352 mm/hr and a soil moisture mean of 9.7%. Table 4.13 indicates that Isu Njaba has higher silt/clay contents than Amucha, again, this factor may possibly be contributing to the higher infiltration rates in non-vegetated land-use class in Amucha compared to Isu Njaba.

Table 4.13: Particle size distribution analysis showing higher sand content at all sites, source, Loraj Consortium (2019).

Location	Particle size distribution		
	% sand	% gravel	% fines (silt/clay)
Amucha	88	4	8
	85	4	11
Isu Njaba	75.9	0.3	23.8
	69.8	1.2	29.0
	78.2	5.3	16.5
	73.8	1	25.2
Obibi-Ochasi	71.8	1	27.2
	72.1	0.7	27.2
	73.8	1	25.2
	74.2	0.3	25.5
	67.8	1.2	31
Umueshi	95.59	1.4	4.41
	96.9	1.5	1.6
	94.06	1.62	4.32
Urualla	95	3.3	1.7
	69.3	5	25.7
	76.5	6.7	16.8
	69.3	5	25.7
	68.5	5.2	26.3

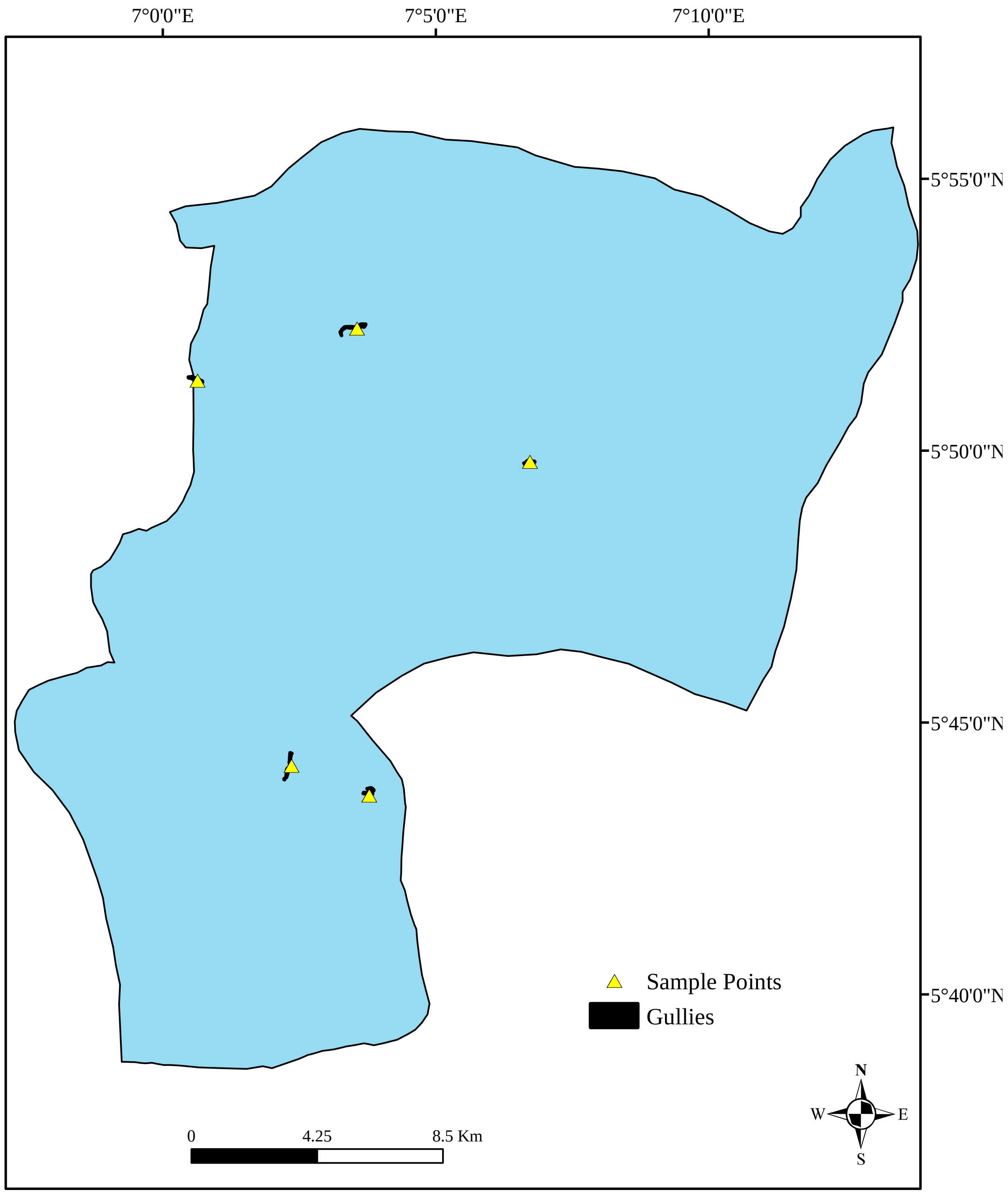

Figure 4.19: Sample sites within the gullies where soil samples were collected for tests. Section 3.2.1.3 gives a detailed approach adopted for soil sample collection and testing

Table 4.14: Density and strength tests. Apart from the cohesion results, other strength parameters have sensible results at all sites, source, Loraj Consortium (2019).

Location	Maximum dry density (mg/m^3)	Cohesion (KN/m^2)	Angle of internal friction (°)	Shear strength (KN/m^2)
Amucha	1.94 1.94	2 2	27 26	92.6 88.7
Isu Njaba	1.68 1.68 1.65 1.61 1.68	2.6 5.8 11.5 7.8 10.7	20.2 21.9 22.3 21.4 20.1	84.9 71.8 87.9 79.5 93.6
Obibi-Ochasi	1.76 1.78 1.79 1.78 1.82	5.2 7.2 4.1 9.2 0.8	26 26.80 24.01 25.26 31.2	98.8 97.8 95.8 97.8 100.2
Umueshi	1.92 1.83 1.93	- - -	37.6 36.8 36.5	- - -
Urualla	1.80 1.80 1.90 1.90 2.00	1 5 5 7 6	33 30 25 25 25	116.46 107.0 87.9 89.91 88.91

Table 4.15: Infiltration rates of different land-use classes in the study area. Non-vegetated soils in Amucha have the highest infiltration rates in the study area. Amucha study site has the highest sand content across all study sites. Section 3.2.1.3 details methods used for infiltration tests.

	Open vegetation		Fallow/trees		Non-vegetated	
Amucha	Infiltration (mm hr^{-1})	Soil moisture (%)	Infiltration (mm hr^{-1})	Soil moisture (%)	Infiltration (mm hr^{-1})	Soil moisture (%)
	12.81	3	37.69	9.2	57.2	
	10.49	3.6	56.62	3.7	257.4	
	246	13.6	258.7	10.5	264.24	8.6
	419.68	14.5	225.97	15.7	661.69	12.3
	48.63	10.2	237.04	11.4	455.21	11.4
	67.51	14.7	152.6	12.1	416.37	6.3
Isu Njaba	12.32	10.6	2.42	18.3		
	17.16	6.1	5.82	19.9		
	17.77	11.6	7.78	23.3		
	15.05	13.4	4.62	20.2		
	39.44	18.3	14.8	9.9		
			10.85	20.7		
Obibi-ochasi	77.9	8			49.51	9.3
	142.2	9			48.59	9.1
	84.88	11.1			47.22	10.3
	78.39	8			115.65	8.7
	130.85	8.4			105.72	8.4
	117.54	9.4				
Umueshi	5.12	5.6				
	23.12	4.5				
	45.98	7.3				
	91.67	7.8				

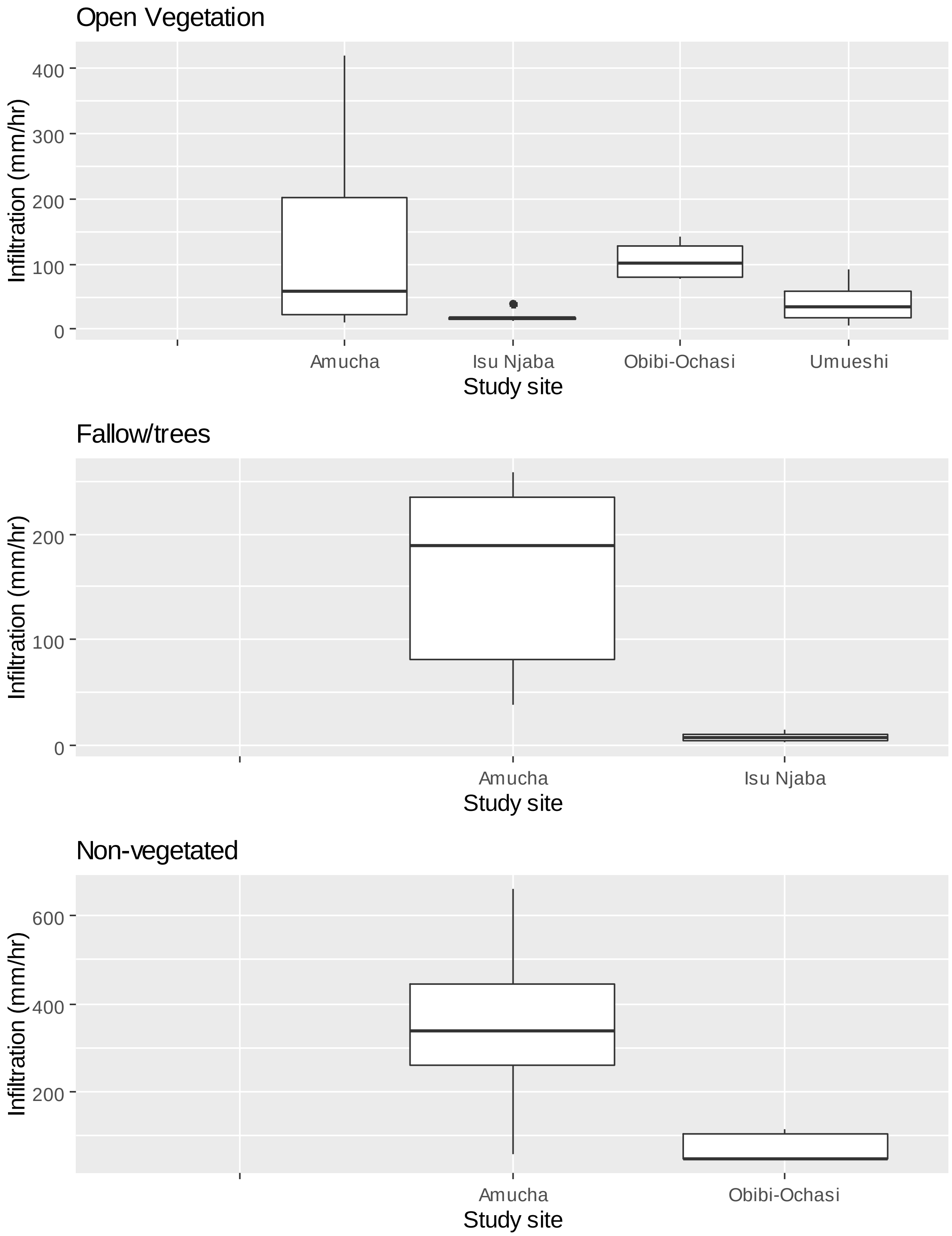

Figure 4.20: Boxplots of infiltration capacities for the three land-use classes. Mean infiltration rate for non-vegetated soils in Amucha was highest (352 mm/hr) across all land use types.

4.4.2 Human-induced elements and community perceptions

Results from focus group meetings (section 3.2.1.3) showed that civil unrest is a driver of gullying. Group meeting participants maintained there were no gullies in the study area before the Nigeria-Biafra civil war which lasted from 1967 – 1970. Based on focus group meetings and interviews, the oldest gullies in the area are found in Amucha, Obibi-Ochasi, Urualla, Umueshi and Isu Njaba (Figure 4.21), these communities are found in Njaba, Orlu, Ideato North, Ideato South and Isu LGAs accordingly. Focus group discussants said that the Amucha and Obibi-Ochasi gullies started in 1969 and 1968 respectively. Information from interviews with community members indicated that the Urualla, Umueshi and Isu Njaba gullies were thought to have been initiated during same time (1968 – 1970). Participants at focus group meetings attributed gully initiation under the civil war era to the following factors:

I. Sudden increase in population density: The Orlu area, provided shelters for displaced war refugees from other parts of southeast Nigeria as the war did not get to the Orlu region of the country. This situation was the reason the Orlu area played host to the headquarters of the Organisation of African Unity (OAU) that ran humanitarian relief agencies during the civil war. The Nigerian headquarters of the British Cheshire Home was also located in Orlu and hence, there was sudden increase in human population in these safe havens. As the population density suddenly increased, original forests were disturbed by refugees due to search for food and shelter. Focus group participants in Amucha attributed this forest disturbance coupled with the natural topography of the land which channelled surface runoff from other communities in the Njaba River upstream such as Eziama, Eziachi, Umudike and Umuowa to the Njaba River through Amucha (the Njaba River rises from four communities; Amucha, Eziama, Isu Njaba and Ekwe) to the outset of gully erosion in their community.

II. Military activities: Two gullies were found in Obibi-Ochasi and results from the focus group meeting in the community suggest the older gully started at the Okpii stream in 1968 due to a number of factors including military activities during the war. During this time, the Biafran Rangers (a group of Biafran soldiers) used the Okpii waterfall as a shooting range for training their soldiers. Numerous bunkers were dug as well, all aimed at training the soldiers, thus, the Orlu area did not only serve as home for humanitarian agencies and refugees, it was also used as training grounds for soldiers. One elder from the focus group meeting asserted “in 1968, there was a heavy rainfall”. These bunkers which were never covered after the war could have likely created the first artificial channels for runoff, thus, setting the stage for possible gully initiation. Based on these replies, it was possible that military infrastructure including bunkers and shooting ranges, coupled with the heavy rainfall of 1968 marked initiation of the older gully in Obibi-Ochasi community. The younger gully was said to be less than two years old at the time of fieldwork.

III. There is also the story of the desecration of the stream and killing of sacred pythons by Biafran soldiers during the war. Within the study area, some animals are not hunted or killed out of respect for the customs and traditions of the people, one of such animals being the sacred python. Also, fishing is forbidden in some sacred streams as animals in such streams belong to the local deity. However, due to scarcity of food, or non-familiarity with the customs of the people, or other war time conditions which led to disregard of the laws of the land, sacred pythons were killed by the soldiers who also fished in the sacred river. These two activities of desecration are believed by some in Obibi-Ochasi to be the reason for the onset and growth of the older gully. It is assumed that the current gully problems are signs of anger by the gods of the land who have showed their wrath to the community for disrespecting them and killing the holy animals.

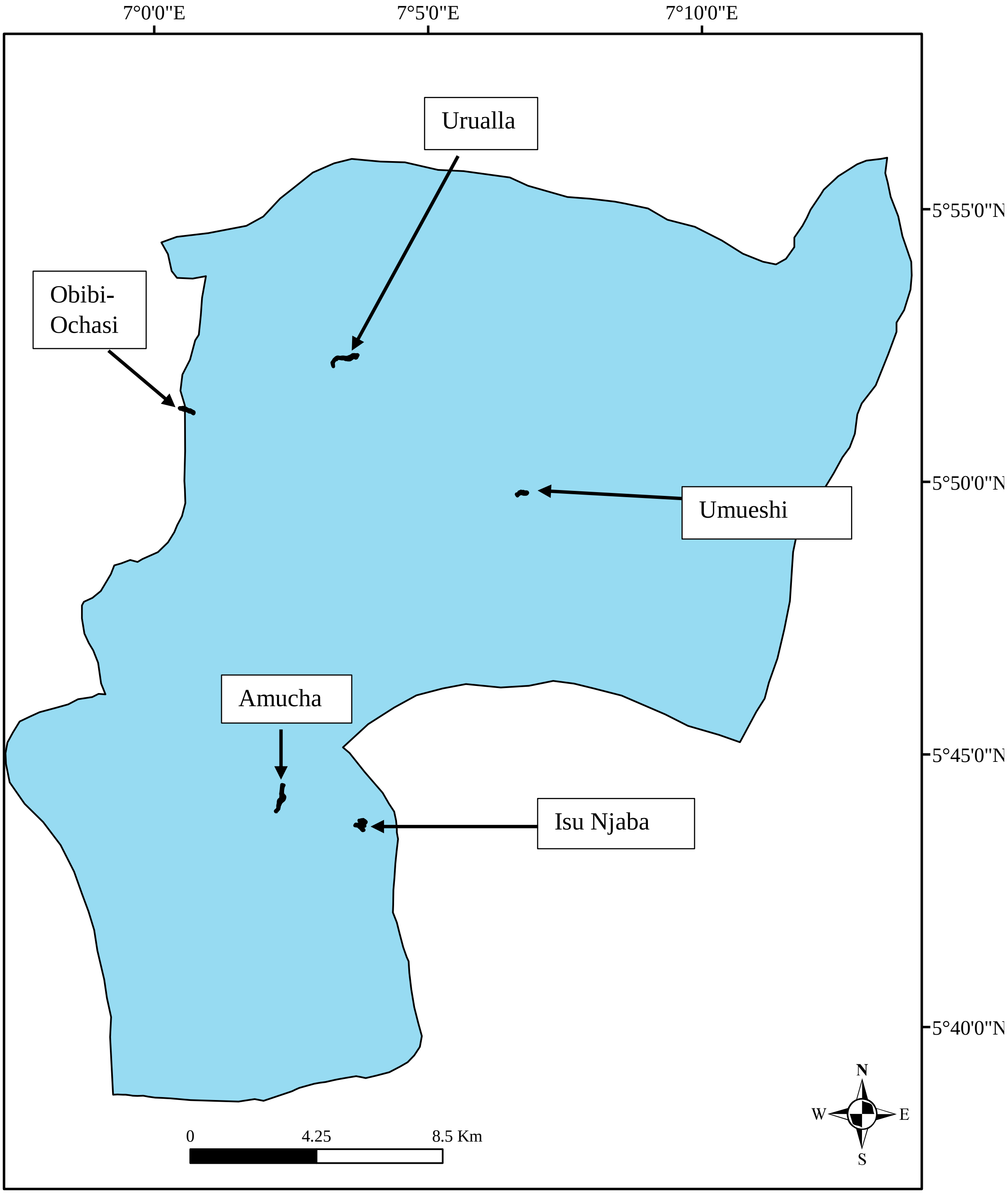

Figure 4.21: Gullies that started as a result of the Nigeria-Biafra civil war. The Amucha gully started in 1969 while the Obibi-Ochasi gully has an initiation date of 1968. The other gullies are said to have started round about same time.

4.5 Discussion

4.5.1 Land-use changes

Three land-use classes were identified in this study: non-vegetated, open-vegetation and fallow/tree cover and to improve confidence in the land use maps produced, accuracy assessments were undertaken. The accuracy assessment results reported here (Tables 4.2 and 4.3) are higher than some results published in the literature, for example, Appiah et al. (2018) reported an overall accuracy of 72% and kappa statistics of 0.59 (59%) for land cover classification in the Bosomtwe Range Forest Reserve, Ghana. Also, Yan et al (2015) reported an overall accuracy of 83% and kappa statistics of 0.79 in their classification of vegetation cover types in Northeast China. Although, the number of land use classes identified by these authors vary from those classified in this study, my classifications are suitable for land use types found in the study area, and for the aim of the study.

Previous authors have documented sustained land-use changes, especially, changes from vegetated to paved surfaces in parts of southeast Nigeria (Enaruvbe & Ige-Olumide, 2015; AC-Chukwuocha, 2015; Enaruvbe & Atedhor, 2015; Njoku et al. 2017), and results presented in this study support these claims. Of the 22 delineated gully catchments, reduction in fallow-cover was observed in all but IdSouthWS1 gully catchment. Regarding increase in non-vegetated surfaces, NjabaWS1 and IdSouthWS1 catchmnets experienced reductions in bare surfaces while the remaining catchments experienced increases in land areas under non-vegetated class. Thus, while entire study areas could experience changes from one land use class to another, changes in individual catchments differ, which might potentially affect gullying.

4.5.2 Changes in gully characteristics

Poesen et al. (2003) identified three stages of gully evolution according to their age since initiation: short (< 5 years), medium (5–50 years) and long term (> 50 years). According to focus group discussants, the oldest gullies in the study area started during the Nigeria civil war between 1967 and 1970. Apart from these five gullies (figure 4.21) which can be regarded as long term, the others are short to medium term gullies. The gully head retreat rate between 2009 and 2018 reported for the 39 gullies under investigation in this study (4 m yr^{-1}) is low compared to other studies in southeast Nigeria where gully retreat rates of between 30 – 60 m are known and documented (Egboka et al. 1985; Hudec et al. 2005). However, the number of gullies or years of study for these reported results are not known. In other parts of the world, different retreat rates have been documented e.g. Frankl et al. (2012), documented retreat rates of 0.34 m yr^{-1} for gullies less than 5 years in the Ethiopian northern highlands; Hu et al. 2007, measured retreat rates of 0.35 – 7.7 m yr^{-1} in northeast China for young gullies; Liu et al. 2019, reported retreat rates of 0.46 and 1.10 m yr^{-1} for two gullies in southern China. Gully length retreat rate of 182.7 m yr^{-1} was recorded for a short-term period in the Akusity watershed, Upper Nile Basin of Ethiopia (Yibeltal et al. 2019). This rate of change in gully length was attributed to the topography and non-availability of soil and water conservation techniques in the Akusity watershed. In the medium-term scale, Li et al. (2012) documented retreat rates of 0.36 to 0.44 m yr^{-1} in the loess region of China while an annual rate of 115 m yr^{-1} was reported in the long-term scale in north-east Hungary (Gábris et al. 2003). Differences in rainfall regimes, ecogeomorphic interactions, number of sample size and age of gullies account for the variations in retreat rates between those reported in this research and cited references.

Regarding variability in headward retreat rates over time (2009 – 2014 and 2014 – 2018) among the seven gullies identified in 2014, gully retreat rates varied according to ages. There is a lower headward retreat rate in the four gullies identified in 2009 satellite imagery (6.25 m yr^{-1} and 2.1 m yr^{-1} between 2009 – 2014 and 2014 – 2018, respectively) than the three new gullies mapped in 2014 (48.7 m yr^{-1} between 2014 and 2018). These three "younger" gullies are longer than the four older gullies (figure 4.22).

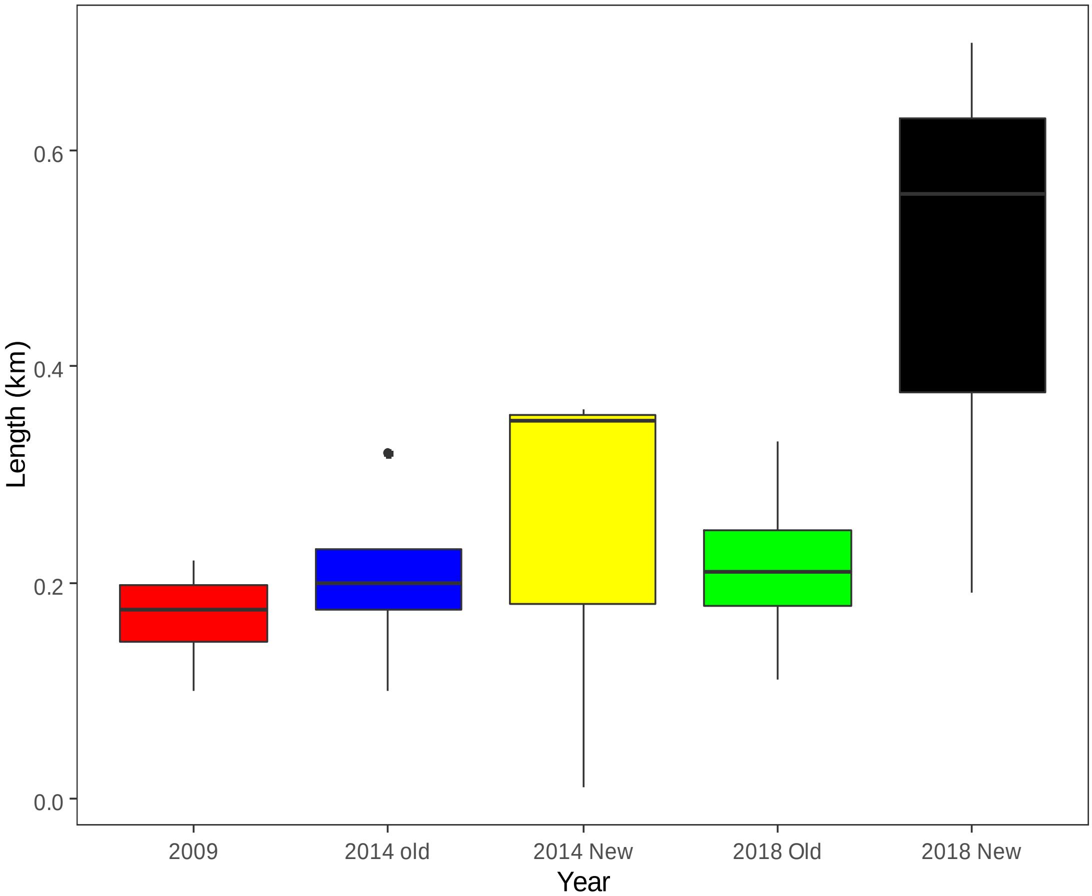

Figure 4.22: Boxplot representing changes in gully length for the seven gullies captured in the 2014 satellite imagery. 2014 old and 2018 old represent the four gullies that were identified in the 2009 satellite data while 2014 New and 2018 New are the three new gullies which were first mapped in 2014.

It is possible the four older gullies are beginning to attain a level of stability (as suggested in section 4.3 for IdSouthWS1, one of the affected gullies with reduced headward retreat rate), hence, the reduction in headward retreat with time. This potential gully stability with time is explained in terms of the differences between retreat rates of 6.25 m yr^{-1} (2009 – 2014) and 2.1 m yr^{-1} (2014 – 2018) for same gullies. Another potential reason for the higher headward retreat rates of the three new gullies is related to land use. Vanmaercke et al. (2016) opined that land uses that promote runoff may also increase gully headcut retreat rates. All three new gullies are closer to tarmac roads than the four older gullies (examples are shown in figures 4.23 and 4.24). The effects of concentrated runoff will be higher on the gullies closer to the roads than those farther from the roads, and hence the faster headward extension of the newer gullies.

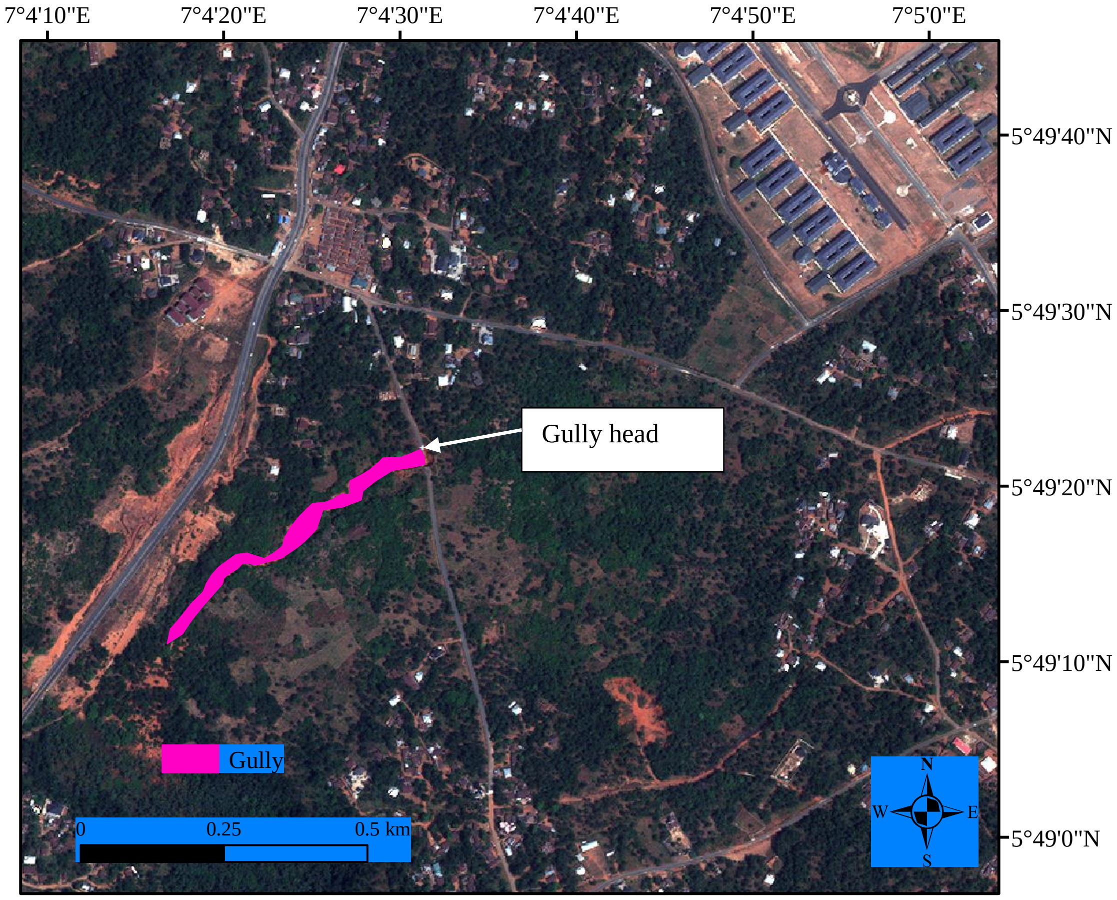

Figure 4.23: 2017 satellite data showing IdeatoSouth_gully2. The gully was first identified in the 2014 satellite data but in 2017, it had destroyed one of the tarmac roads as shown in the satellite data.

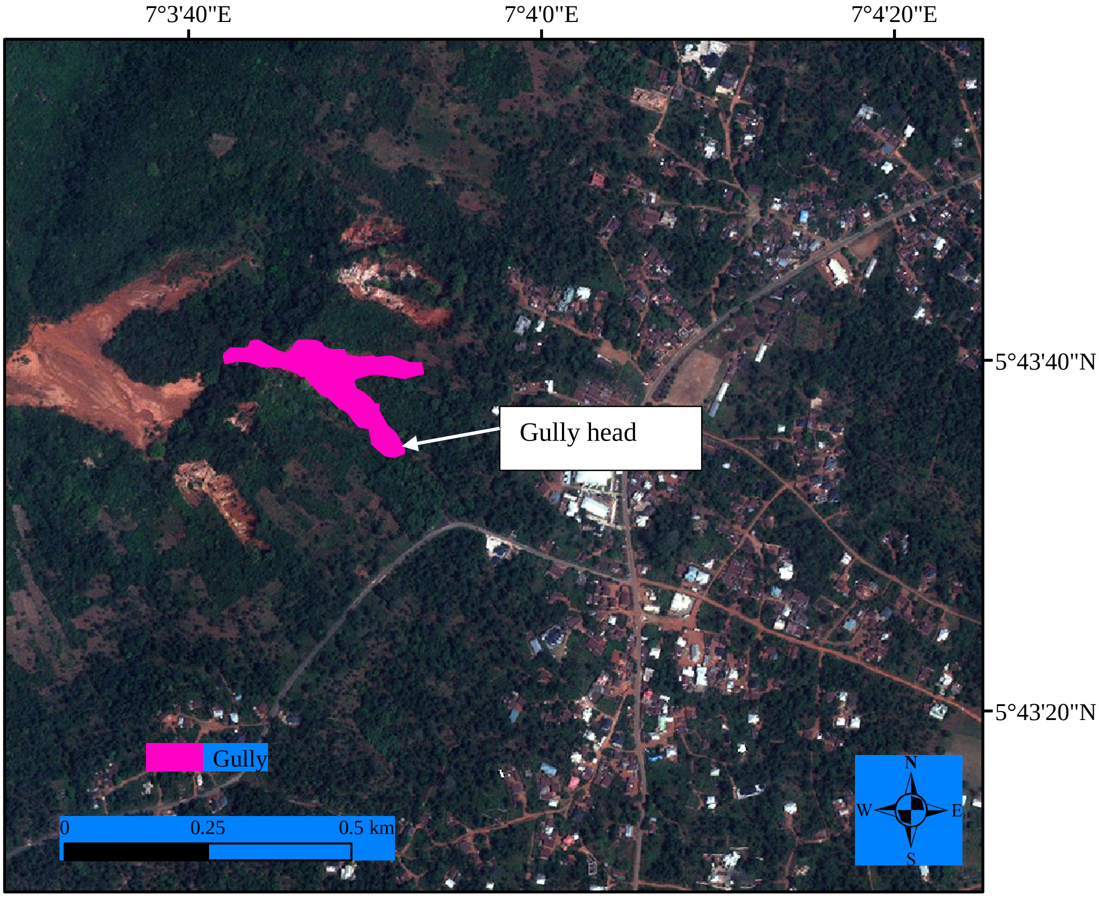

Figure 4.24: 2017 satellite data showing the Isu_gully1. The gully was mapped in the 2009 satellite image but was 150 m from a tarmac road in 2017.

Having answered the first three research questions posed in section 4.0, the last question is posed, how have ecogeomorphic interactions affected changes in gully characteristics? To answer this question, gully-driving factors are grouped into preparatory and trigger factors.

4.5.3 Preparatory factors of gully erosion

In section 4.4.1, results on slope angle, elevation, curvature, proximity to rivers and soil properties were presented. These factors affect gullying through the following processes:

i. Accelerated surface runoff: increased slope (especially around the rivers) will favour accelerated flow of surface runoff. Flow acceleration in contrast to accumulation can be a potential driver of gully erosion in the study area.
ii. Seepage erosion: Considering the high sand contents of the soil (Table 4.13), and consequent high infiltration capacities, increased seepage erosion could be a gully expansion process (Okagbue & Ezechi, 1988). These higher flow rates of sub-surface flow are enhanced by the loose coarse and pebbly sands in the study area (Egboka et al, 1985). Table 4.14 shows that the cohesion values of the soils are low perhaps due to the high sand contents. Therefore, when these soils with low cohesion values are exposed to a sudden rise in slope within a short distance, coupled with the high amount of rainfall (section 3.1.2), there may well be increased susceptibility to initiation of gully, and where gullies already exist due to other factors such as civil war, expansion of those gullies can be facilitated from both surface and sub-surface flows.
iii. Finally, deposited materials, especially at the foot of gully walls, might serve as protective shields, thereby preventing further scouring of gully walls. However, where these deposits are carried away by ephemeral flows and deposited in the rivers due to the nearness of the gully endpoints to the rivers (Figure 4.18) (Conoscenti et al. 2014), a positive mechanism of constant removal of soil from gully upslope will likely be initiated. Thus, as more materials are removed by the river, even more deposits are supplied by the gully.

These three identified processes are the likely reasons gully head distance from rivers has a positive effect on changes in gullied areas (Table 4.9).

4.5.4 Trigger factors of gully erosion

Trigger factors considered include land-use changes, incorrect termination of drainage channels and abandoned projects. Land-use change, particularly, change from vegetated surfaces to non-vegetated surfaces, increase flow of runoff (Njoku et al. 2017) and likely increase in the incidence of gully erosion (Attah et al. 2013). The effect of land-use change on surface runoff will be most felt on areas with higher slope rises, for example, communities close to the rivers and where drainage channels are terminated wrongly by contractors, or where construction projects are completely abandoned.

In some gully catchments close to the river, e.g. Amucha, there have been changes in land use from vegetated to non-vegetated (Table 4.4). This observation was supported during the focus group meetings where respondents agreed and pointed that increased paved surfaces have led to higher volume of surface runoff over the years (section 7.11). A similar report was given by respondents in Obibi-Ochasi. Bearing in mind the configuration of the land and rise in slope from rivers (figure 4.14), increased volume of surface runoff from these surrounding communities can attain higher erosive power as it approaches the river (Gómez-Gutiérrez et al. 2015). This increased surface flow (caused by both change in land use and higher slope rise) passing through gully channels on its way to the river, can enhance gully expansion.

With regards to incorrect termination of drainage channels and their effects on gully erosion, Nwankwor et al. (2015) noted that soils in southeast Nigeria were not easily erodible as is hitherto believed. They concluded that most gullies in the region can be traced back to improper termination and unplanned diversions of road runoff concentration. Other authors (Collison, 2001; Frankl et al. 2012) have documented the associations between gullies and nearness to roads. Figure 4.12 shows pictures of gullies that were observed during fieldwork; depicted gullies have eroded into the asphalt roads next to them. Figure 4.12A is a gully in Okwudor community, Njaba LGA and judging from interview with locals, it was gathered that the gully was reactivated due to new construction activities on the Orlu – Owerri highway. Figure 4.12B is a new gully located in Obibi-Ochasi Community of Orlu LGA and based on eyewitness account and information gathered during focus group meetings, the gully started in 2017. Field measurement puts the gully length at 492 m and 55 m wide at its widest area, as at May 2019, during fieldwork when the pictures were captured (figure 4.12B). This gully started as a result of abandonment of road construction linking two adjacent communities, Asa-Ubirielem in Orsu LGA and Obibi-Ochasi in Orlu LGA. Different types of gully-induced landslides were observed at this gully (section 6.12). During field work, residents of Umueshi community attributed the destruction of their local road (figure 4.12C) to the high volume of surface runoff that flows into the gully following abandonment of gully restoration project.

4.6 Chapter summary

The aim of this chapter was to understand the influence of land use and land-use changes on gully characteristics, and to achieve this aim, four research questions were raised. It has been shown that within the period under investigation, land use has changed, and gully characteristics have also changed. Figure 4.25 provides an interpretative overview for this chapter. The infiltration tests and soil particle results of the study area suggest there is high infiltration which suggests the likely influence of seepage erosion as a mechanism of gully expansion. Preparatory factors of gully erosion such as high slope angle can increase volume of runoff, while high sand content may enhance infiltration. Both surface runoff and infiltration are parts of the hydrologic cycle of the gully catchment. Trigger factors such as increased bare surfaces due to changes in land use will also affect the gully catchment hydrology by influencing an increase in the volume of surface runoff occurring within the gully catchment. As observed earlier, many gullies are close to the rivers and serve as channels through which surface flow leaves the catchment. Therefore, an increase in surface runoff volume due to land use change means more water will flow through the gully, which may then lead to gully expansion.

It was observed from focus group meetings that the Nigeria-Biafra civil war was the principal trigger of gully erosion in the study area, and this is the first time the role of civil war is examined as a gully driver in the study area. While military activities such as digging trenches could have set in motion the process of gully erosion, heavy rainfall was required to drive the mechanism of subsequent gully expansion.

4.7 Conclusions

The following conclusions are made:

i. While acknowledging there have been major land-use changes, especially, from vegetated to non-vegetated surfaces in the study area, gully catchments are heterogenous. Increase in vegetal cover was observed in some catchments. These variations in land uses likely affect gullying.

ii. Interactions among ecogeomorphic factors (physical and human-induced) influence changes in gully sizes (figure 4.25). While factors such as soil characteristics and slope gradient predispose the soils to erosion, forcing factors such as war-time activities trigger gullying.

iii. There were no gullies in the study area before Nigeria-Biafra civil war, thus, the war can be regarded as the principal trigger of gully erosion in the area.

Having observed from the foregoing that gully catchment hydrology is an important factor in gully erosion studies, the next question is, how have land-use changes affected gully catchment hydrology? Answers to this question will be provided in the next chapter.

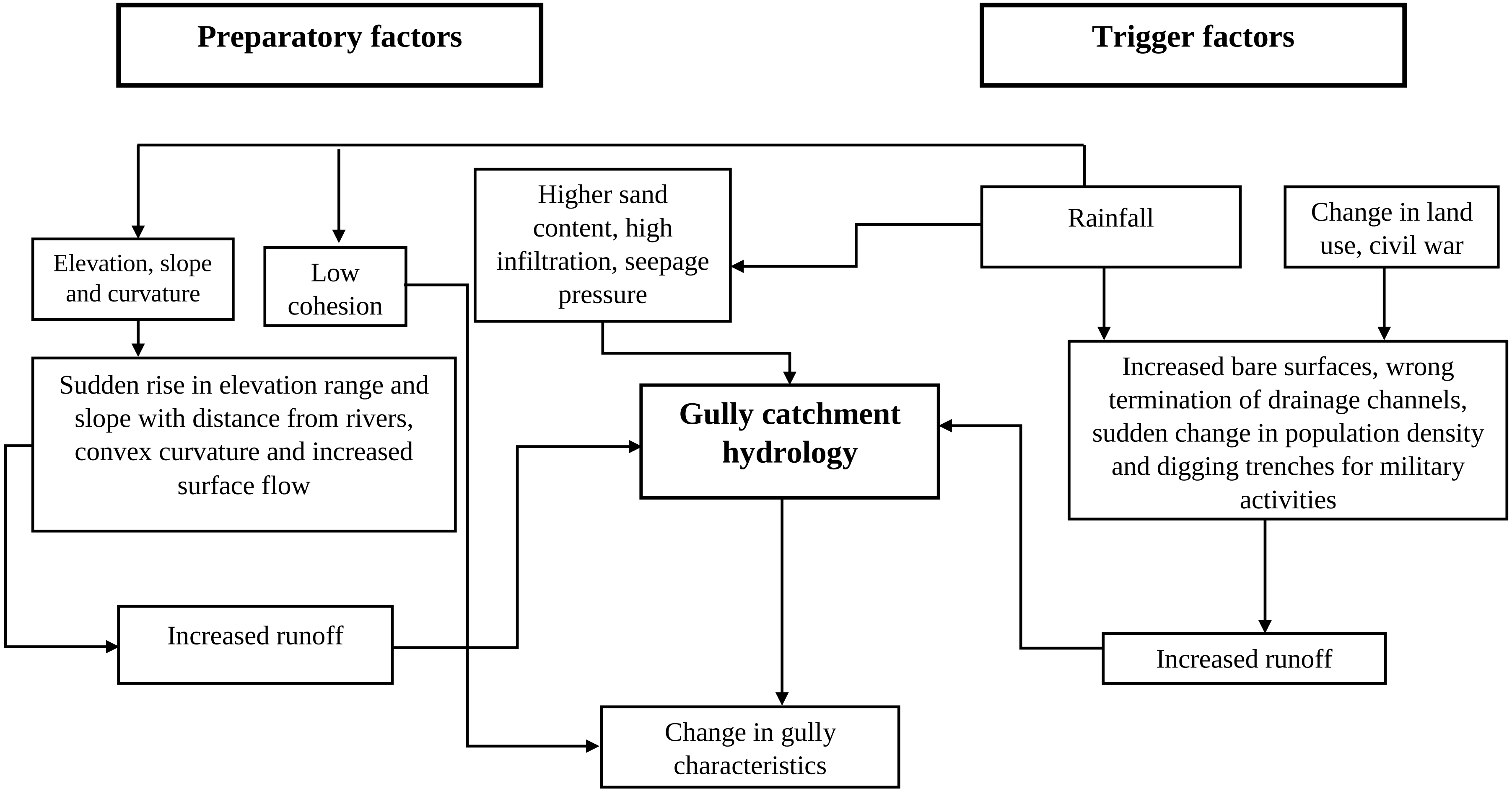

Figure 4.25: Representation of the connections and interactions between preparatory and trigger factors of the influence of land-use change on gully characteristics. Preparatory factors include geomorphic and soil factors, while rainfall and land use changes are examples of trigger factors.

Chapter 5

Influence of land-use changes on gully catchment hydrology

5.0 Introduction

In Chapter 4, it was established there have been land-use changes in the gully catchments between 2009 and 2018. It was also implied that land-use changes and other gully-driving factors influenced gully expansion by affecting the hydrology of the gully catchment, and thus, the gully catchment hydrology served as an agent through whom gully drivers influenced gully sizes. Chapter 5 provides answers to research questions raised by objective 2: to determine the influence of land-use changes on gully catchment hydrology. The following research questions are posed:

1. Have there been changes in the hydrology of gully catchments between 2009 and 2018 in response to land-use changes?
2. Are there associations between changes in gully catchment hydrology resulting from land-use change and gully sizes?

Section 5.1 summarizes changes in the hydrology of the gully catchments between 2009 and 2018 in response to land-use changes. Result validation is described in 5.2, section 5.3 describes the associations between changes in hydrology and gully sizes while discussions are presented in section 5.4. Chapter summary and conclusions follow in sections 5.5 and 5.6.

5.1 Changes in the hydrology of the gully catchments between 2009 and 2018 in response to land-use changes

A total of 22 catchments (figure 5.1) covering 23 gullies (one catchment, Orlu2, has two gullies as shown in Table 5.1) were modelled using the SWAT model. Thirty-nine gullies were identified in the study area (section 4.2), however, upslope contributing areas were not captured for some gullies due to reasons described in section 4.3. The inability of the flow algorithm in the SWAT model to delineate upslope areas for some gullies could also be due to inherent errors such as point or pixel density, the accuracy of the derived data sets and the interpolation techniques which can create erroneous areas in a DEM (Papaioannou, et al, 2019). The upslope contributing areas for the 23 gullies ranged between 0.06 to 29.31 km^2 (Table 5.1). Results of five hydrological processes: changes in streamflow, surface runoff, percolation, lateral flow and evapotranspiration are presented. Surface runoff, groundwater and lateral flow all contribute to channel streamflow. The influence of surface runoff on gully erosion was identified in sections 2.1 and 4.5.4. Groundwater and lateral flows are both sub-surface flow processes, and previous research has demonstrated that soils in the study area could be susceptible to sub-surface erosion due to their high infiltration capacities and texture (Egboka et al. 1985; Okagbue & Ezechi, 1988).

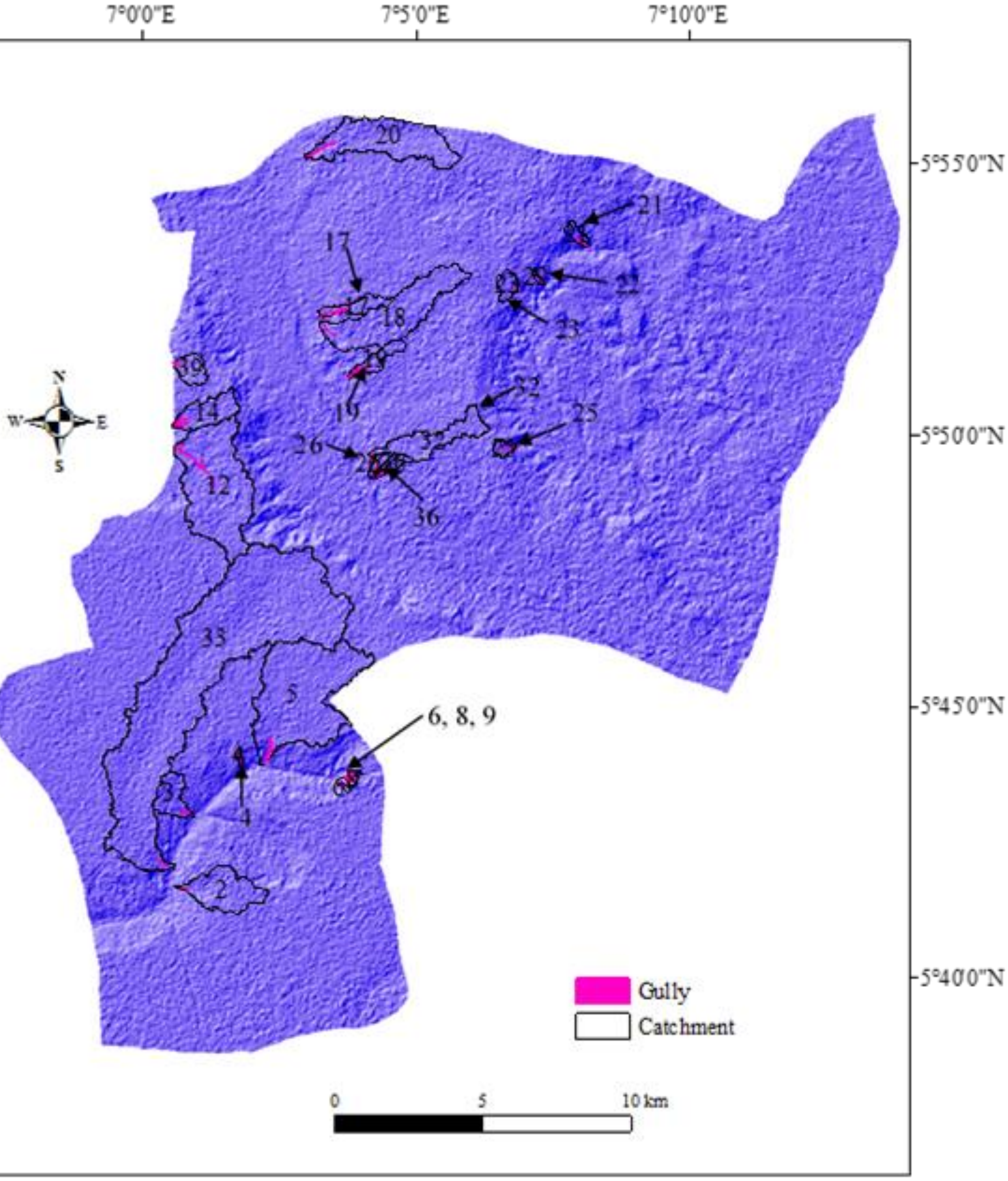

Figure 5.1: 22 gully catchments draped on shaded relief map of study area. Also shown are the gully IDs. Gully IDs are same shown in figure 4.4 and Table 5.1.

Table 5.1: Gully catchment characteristics. Orlu2 has 2 gullies which are <10 m apart in some places. Some catchments have more than one soil class as classified by SWAT.

id	Catchment no.	Gully ID	Size (km^2)	USDA soil type	SWAT soil class
IdNorthWS	1	23	0.53	Sandy loam	Nd19-1a-1557
IdSouthWS1	2	22	0.08	Sandy loam	Nd21-1a-1560
NjabaWS1	3	4	0.13	Sandy loam	Nd21-1a-1560
Amucha	4	5	10.23	Sand	Ph17-1a-6596
IdeatoNorth	5	20	5.01	Sandy loam	Nd21-1a-1560
IdeatoNorth1	6	21	0.35	Sandy loam	Nd21-1a-1560
IdeatoSouth_gully1	7	26	0.26	Sandy loam	Nd21-1a-1560
IdeatoSouth_gully2	8	36	0.31	Sandy loam	Nd21-1a-1560
IdeatoSouth3	9	32	2.33	Sandy loam	Nd19-1a-1557 Nd21-1a-1560
Isu_gully1	10	8	0.14	Sandy loam	Nd21-1a-1560
Isu_gully2	11	9	0.07	Sandy loam	Nd21-1a-1560
Isu_gully3	12	6	0.06	Sandy loam	Nd21-1a-1560
Njaba2	13	3	1.28	Sandy loam	Nd21-1a-1560
Njaba4	14	2	2.78	Sandy loam	Nd21-1a-1560
Njaba5	15	33	29.31	Sandy loam	Nd21-1a-1560
Orlu1	16	12	8.34	Sandy loam	Nd21-1a-1560
Orlu2	17	14,15	1.71	Sandy loam	Nd21-1a-1560 Nd19-1a-1557
Urualla_gully1	18	17	0.85	Sandy loam	Nd21-1a-1560
Urualla_gully2	19	18	5.38	Sandy loam	Nd21-1a-1560
Urualla_gully3	20	19	0.79	Sandy loam	Nd21-1a-1560
Obibi-Ochasi	21	39	0.85	Sandy loam	Nd19-1a-1557
Umueshi	22	25	0.31	Sandy loam	Nd21-1a-1560

5.1.1 Model application in different settings

Results of an ‘exploratory sensitivity analysis’ undertaken to understand the individual influence of land-use changes and rainfall dynamics on changes in catchment hydrology (section 3.2.2.1.10) are presented in this section. The Amucha and Orlu1 catchments (figures 5.2 and 5.4) experienced significant land-use changes from vegetated to non-vegetated (Table 4.4), while the Orlu1 catchment had the highest variability in rainfall for 2009 and 2018, hence, both catchments were suitable for the exploratory sensitivity analysis. Land-use maps and modelled hydrological processes under different settings are presented in figures 5.2 – 5.7. Figures 5.3 and 5.5 show results from same rainfall and different land uses, while figures 5.6 – 5.7 illustrate results for same land use and different rainfall totals.

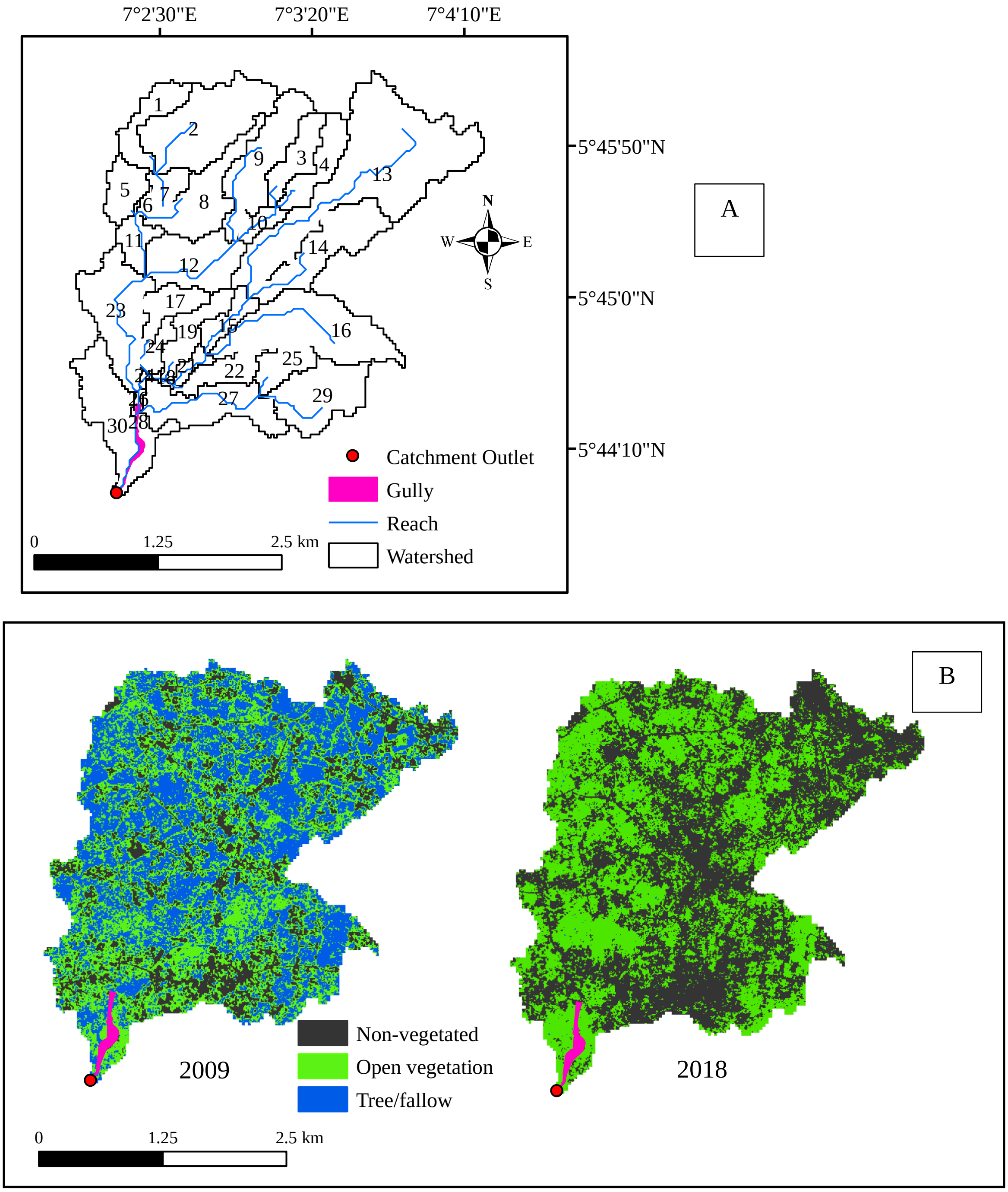

Figure 5.2: A, Amucha catchment showing sub-basins, Gully ID, 5. B, Amucha showing land-use maps. In 2009, Non-vegetated = 17.4%, Open vegetation = 39.2, Tree/fallow = 43.4%. In 2018, Non vegetated = 52.8%, Open vegetation = 47.2, Tree/fallow = 0.1%.

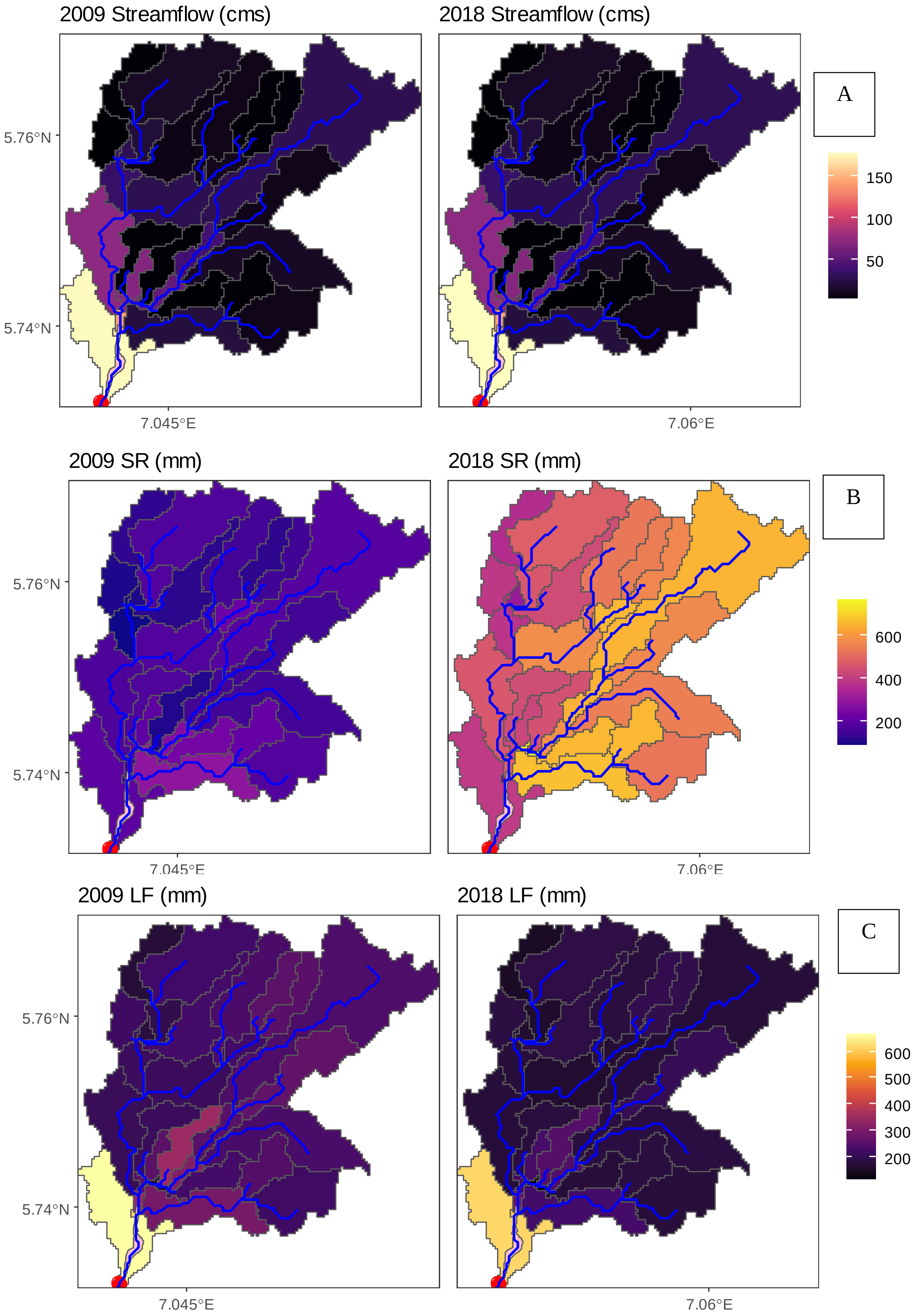

Figure 5.3: Amucha watershed.

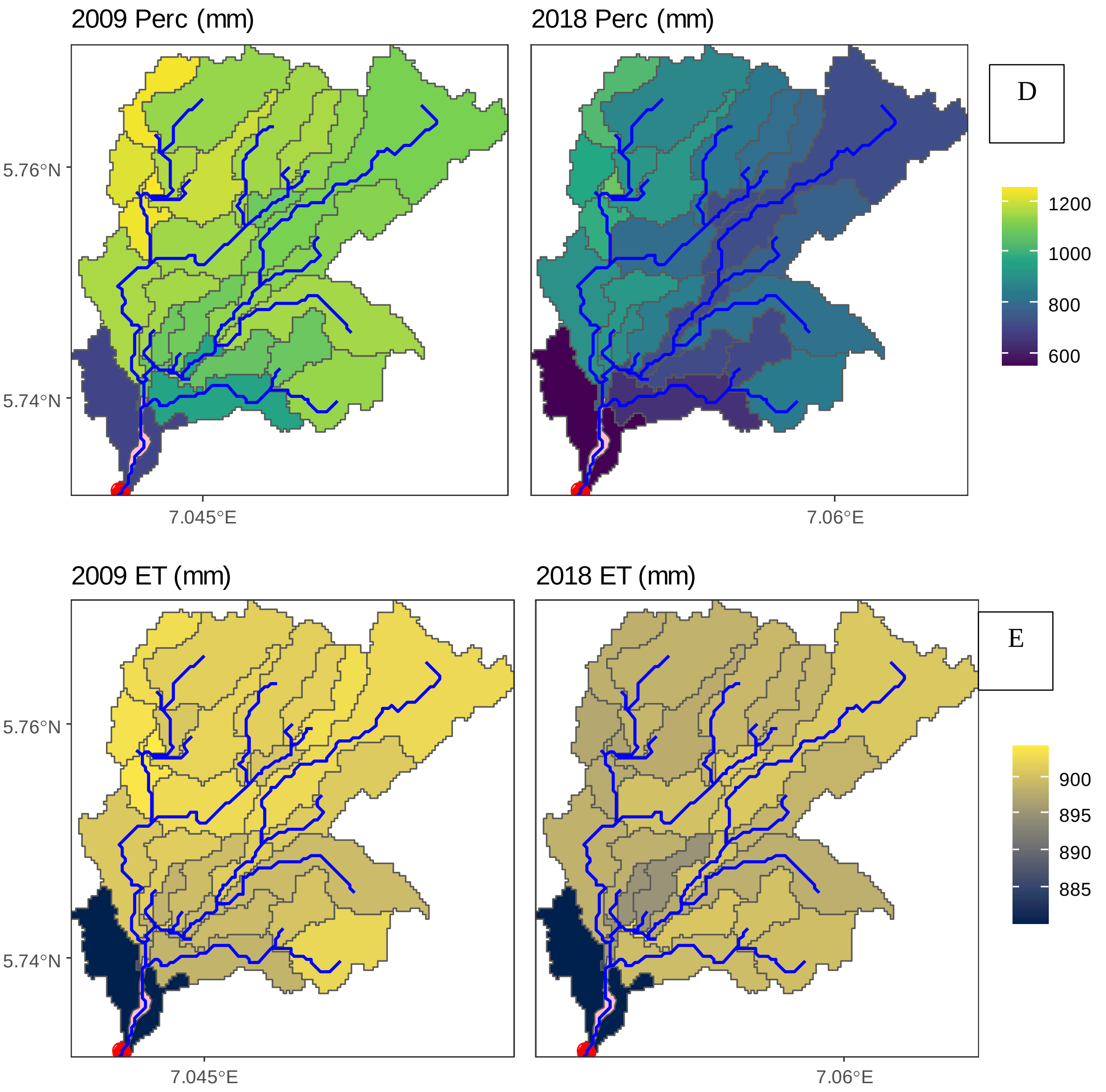

Figure 5.3 cntd: Amucha watershed, same rainfall and different land uses. A, estimated streamflow. 2018 land use had a higher estimate of streamflow (see text for full description). B, surface runoff contribution to streamflow was higher in 2018 than in 2009. C, lateral flow contribution to streamflow is highest in sub-basin 30, same sub-basin covers most parts of the gully. Higher lateral flow volumes were modelled in 2009 than 2018. D, percolation estimates. 2018 percolation estimates were lesser than 2009. E, evapotranspiration. 2009 had higher modelled evapotranspiration volume than 2018. Rainfall for Amucha for both years = 2447 mm. SR = Surface runoff, LF = Lateral flow, Perc = Percolation, ET = Evapotranspiration.

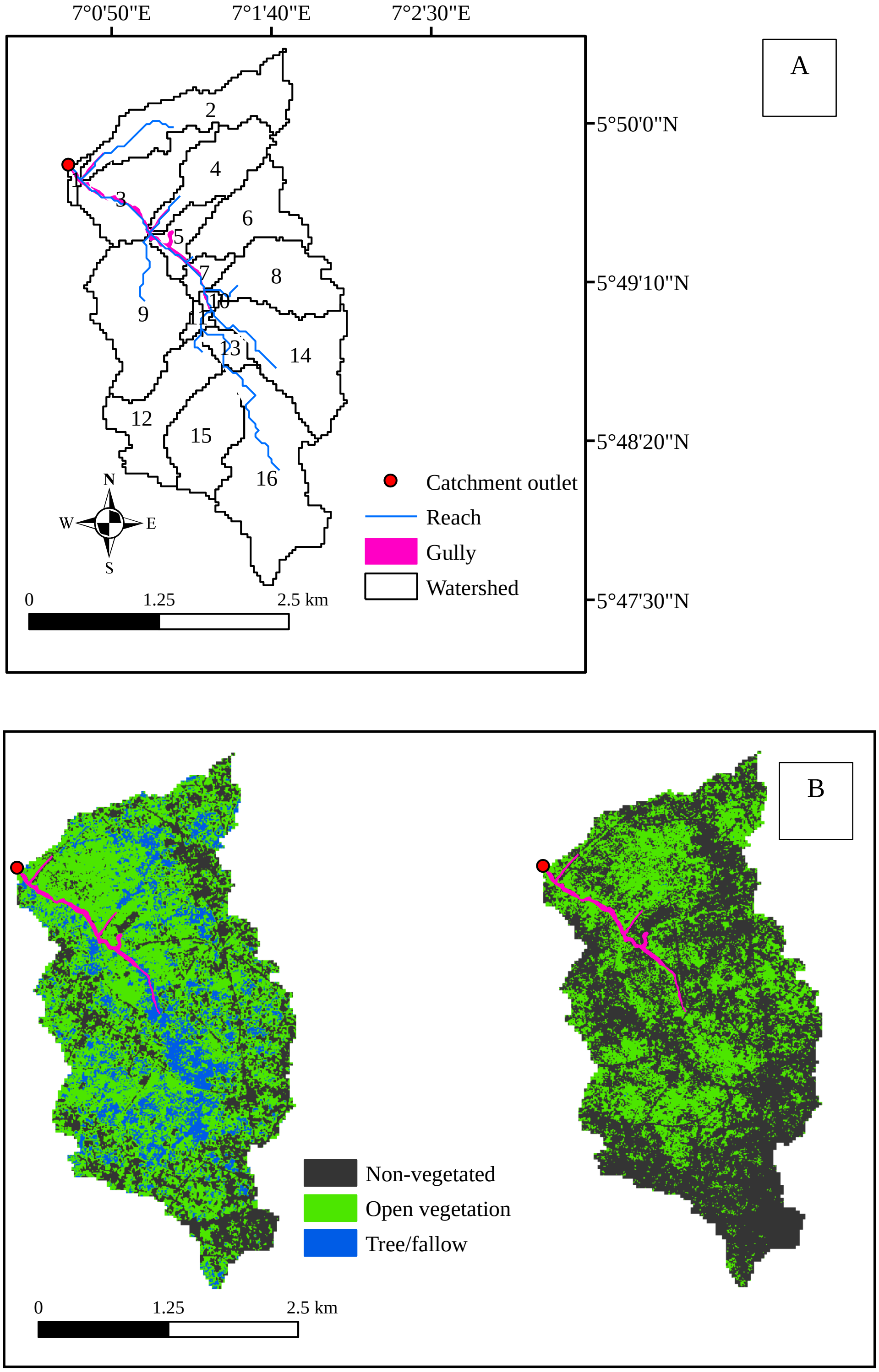

Figure 5.4: A, Orlu1 gully watershed showing sub-basins. Gully ID, 12. B, Orlu1 land-use maps. In 2009, Non-vegetated = 26.18%, Open vegetation = 56.46%, Tree/fallow = 17.36%. In 2018, Non-vegetated = 63.65%, Open vegetation = 36.32, Tree/fallow = 0.03%. Orlu1 is the most urbanised catchment in the study area.

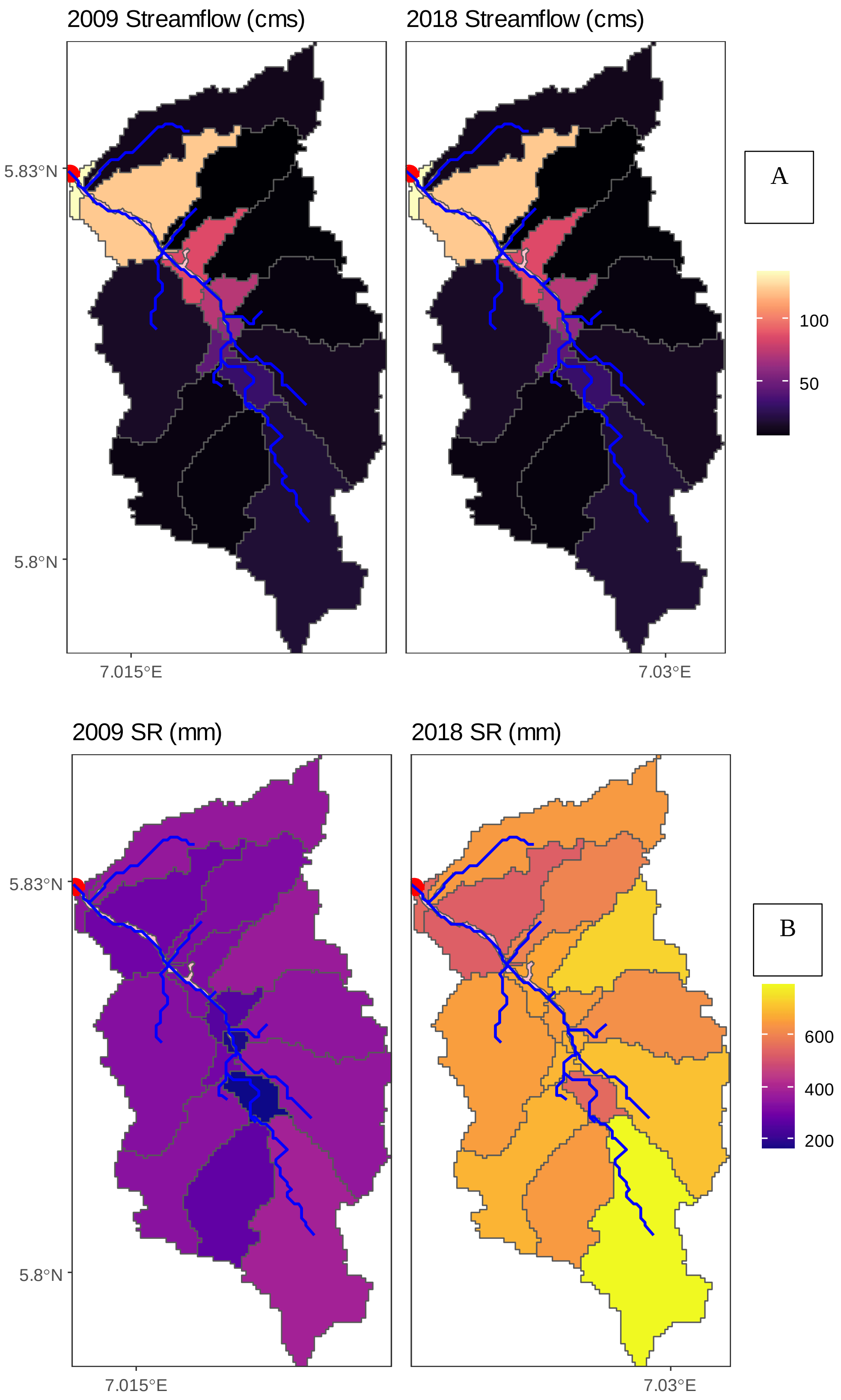

Figure 5.5: Orlu1 watershed

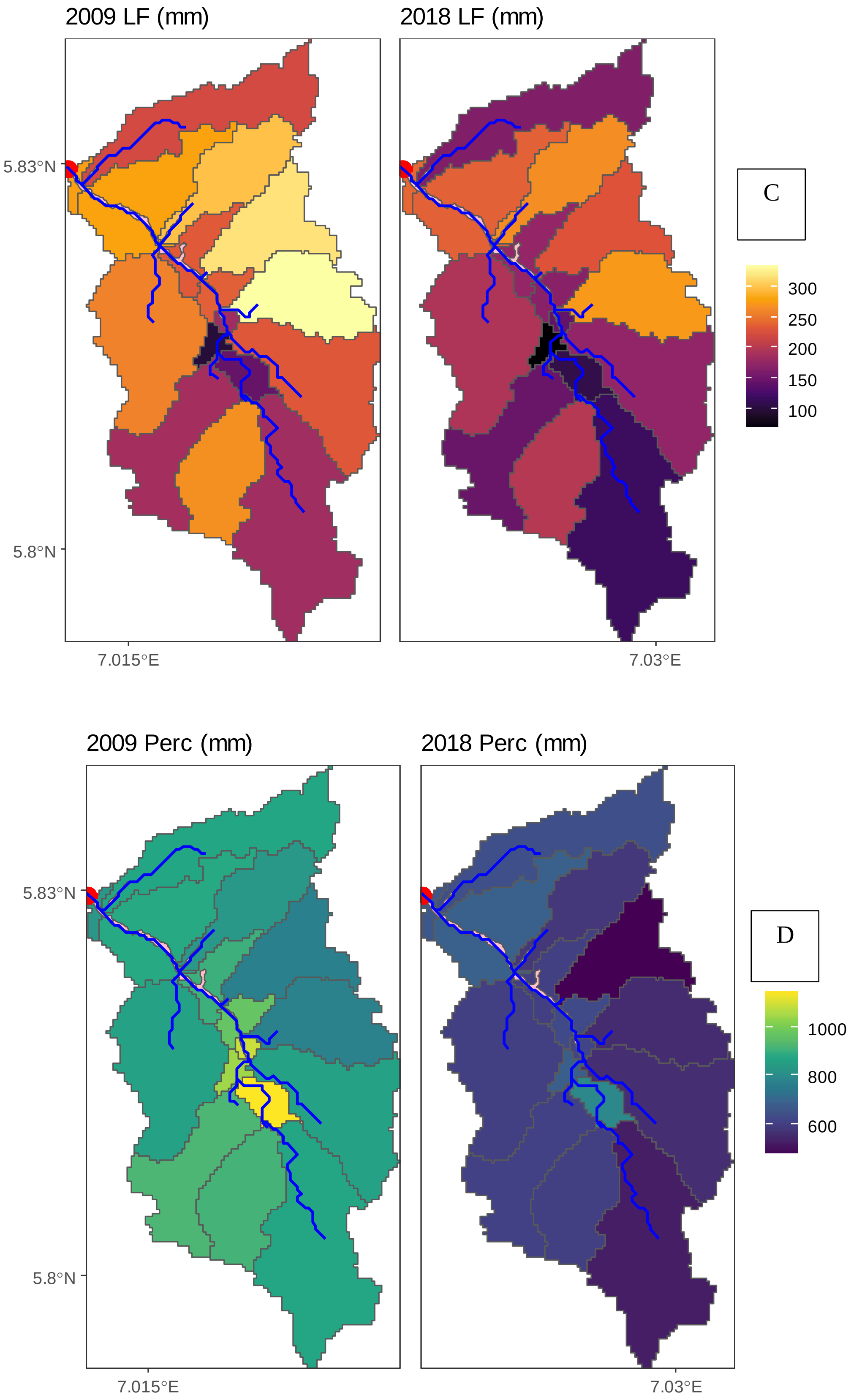

Figure 5.5 cntd: Orlu1 watershed

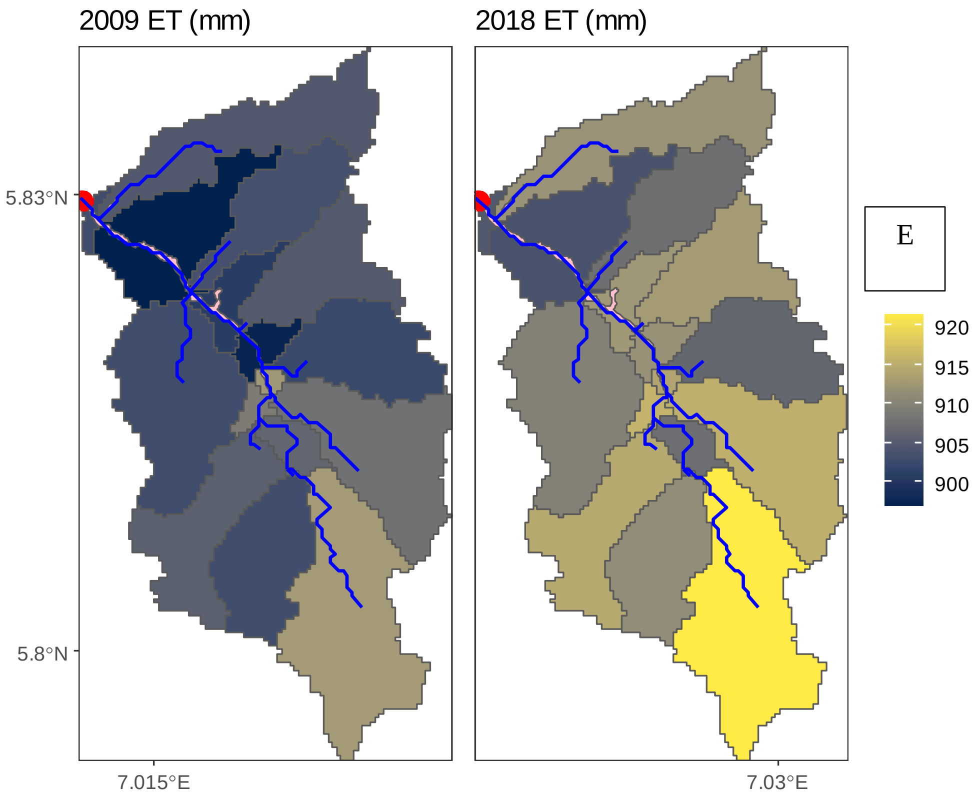

Figure 5.5 cntd: Orlu1 watershed same rainfall and different land uses. A, modelled streamflow. 2009 had higher streamflow volume. B, surface runoff contribution to streamflow increased with increase in non-vegetated class between 2009 and 2018 where higher volumes were modelled in 2018. C, lateral flow contribution to streamflow was higher in 2009. D, percolation estimates. There was a reduction in modelled volumes in 2018. E, evapotranspiration. Modelled evapotranspiration losses were higher in 2018. Rainfall for Orlu1 for both years = 2362 mm.

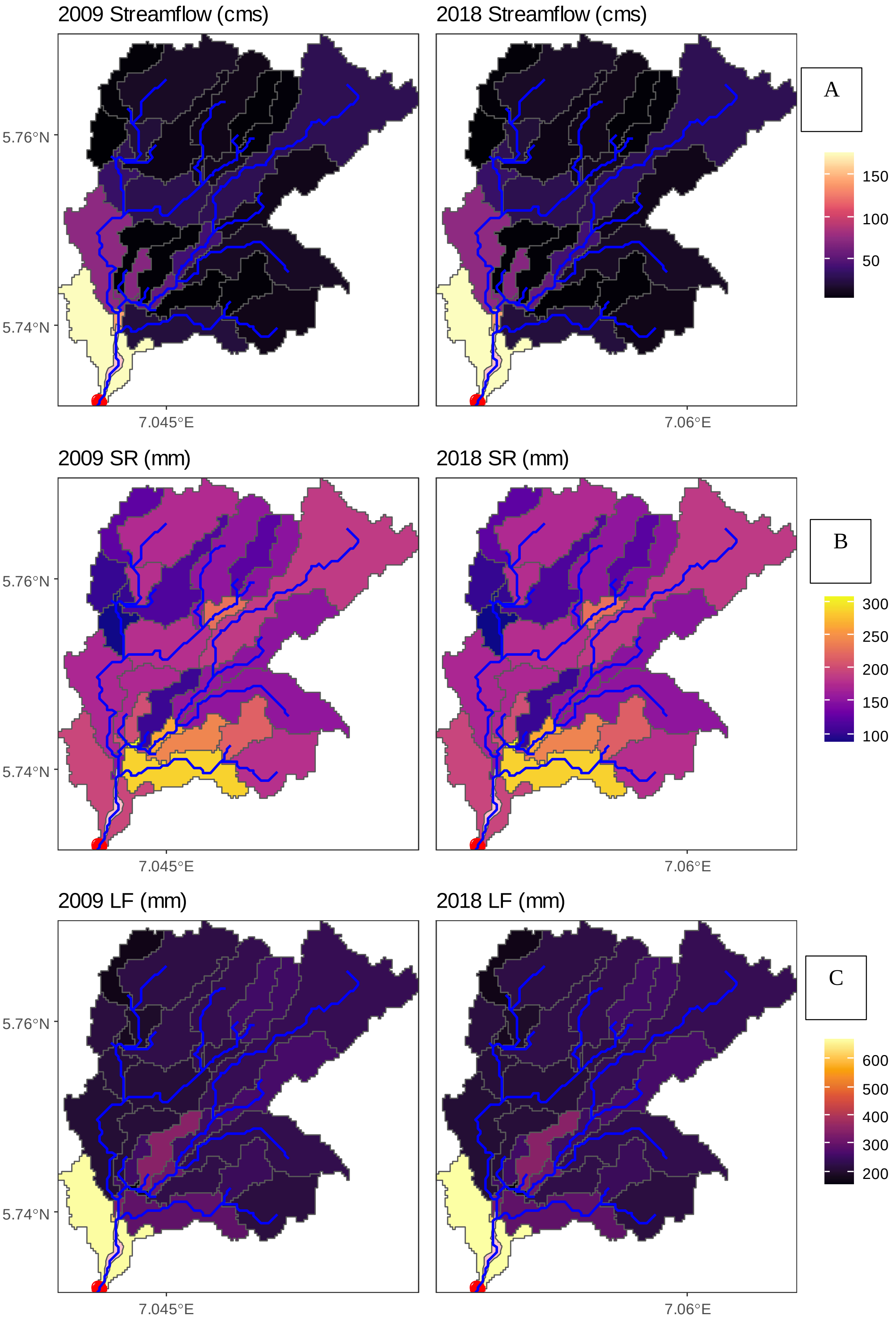

Figure 5.6: Amucha watershed

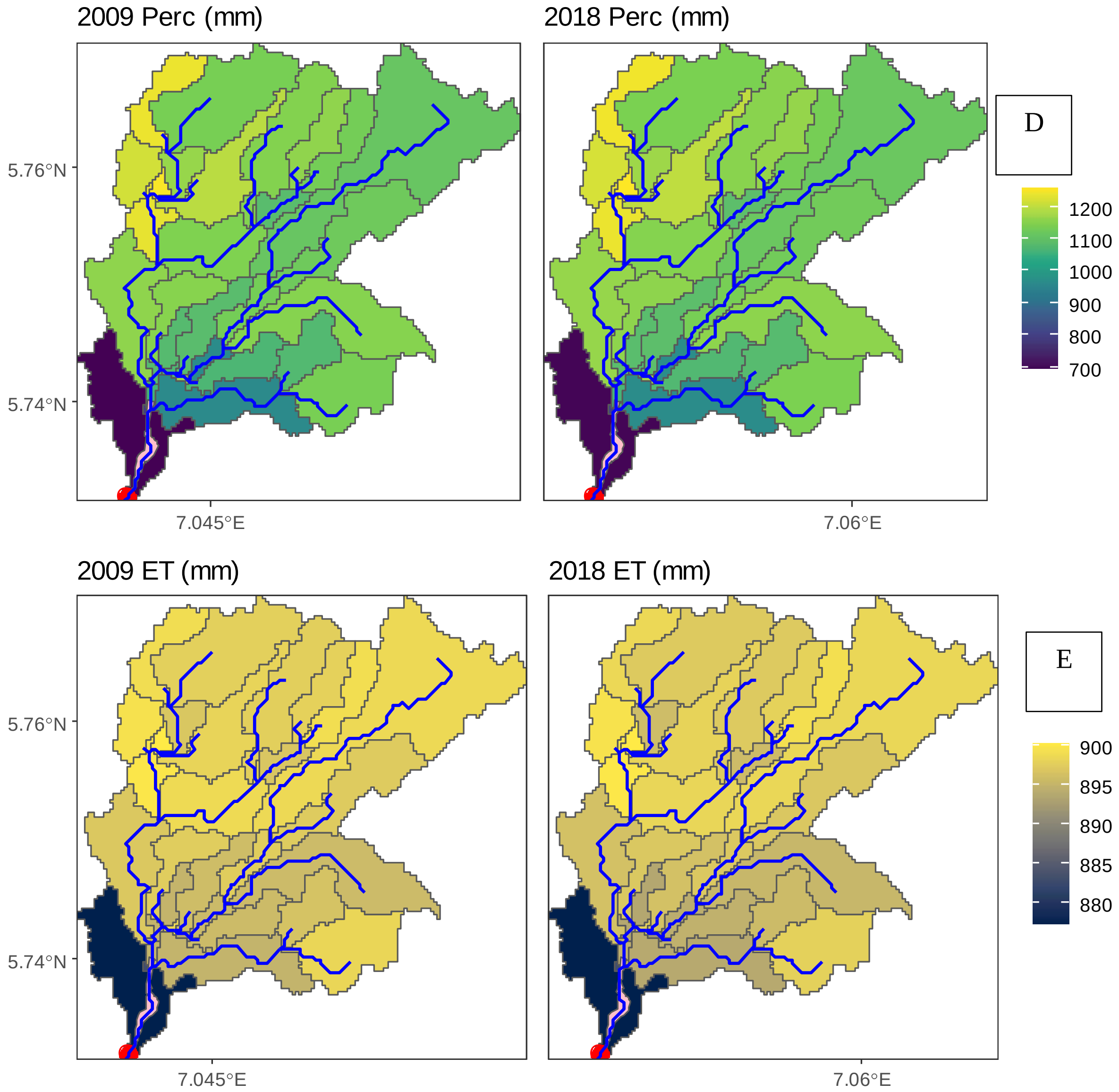

Figure 5.6 cntd: Amucha watershed, same land use and different rainfall totals. A, modelled streamflow. 2018 rainfall produced higher streamflow volume. B, surface runoff contribution to streamflow slightly reduced between 2009 and 2018. C, lateral flow contribution to streamflow. Minimum volumes of lateral flow remained the same for both years. D, percolation estimates. 2018 experienced slightly higher percolation volumes. E, evapotranspiration, maximum loss was higher in 2009. Total rainfall volumes for 2009 and 2018 were 2447 and 2443 mm.

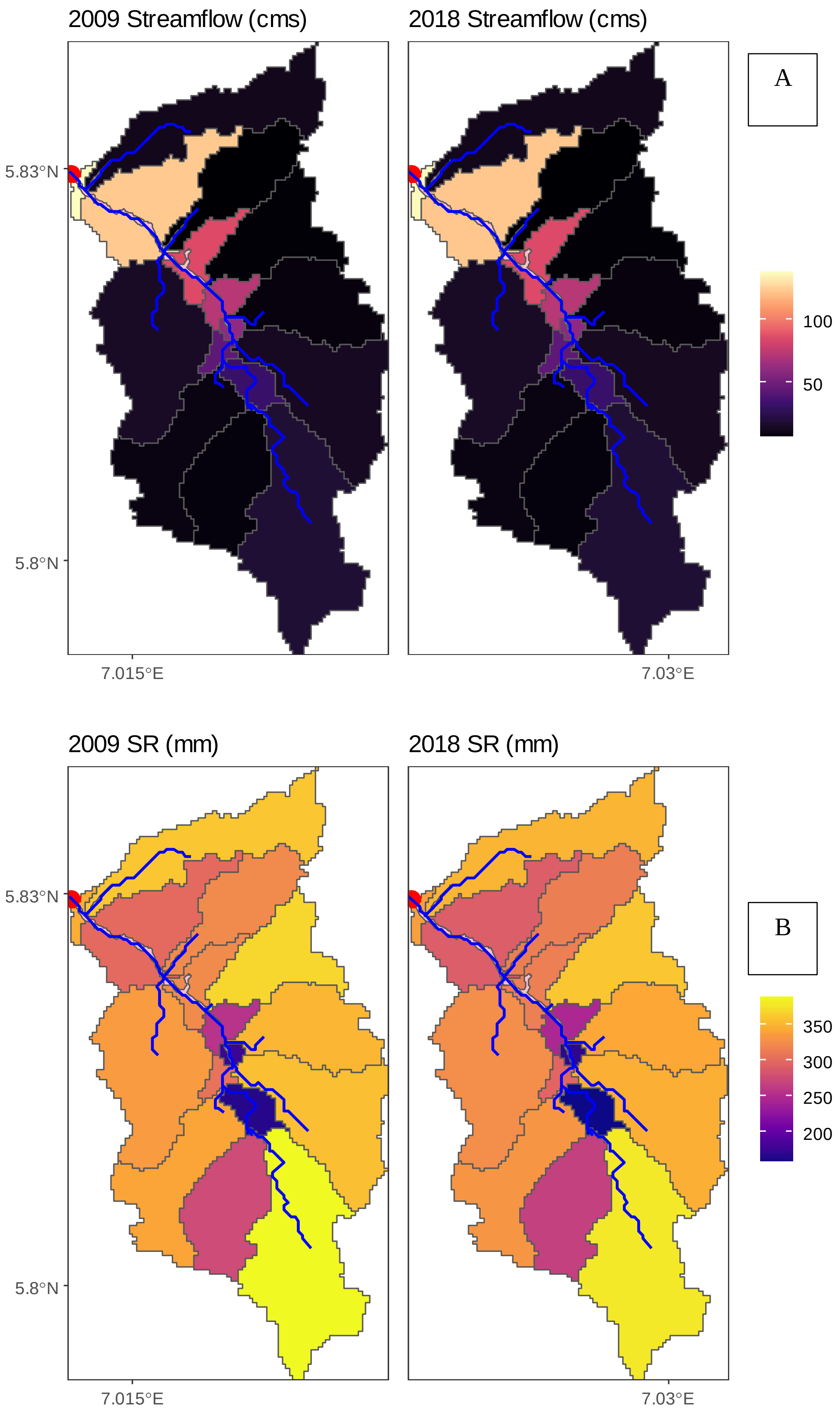

Figure 5.7: Orlu1 watershed

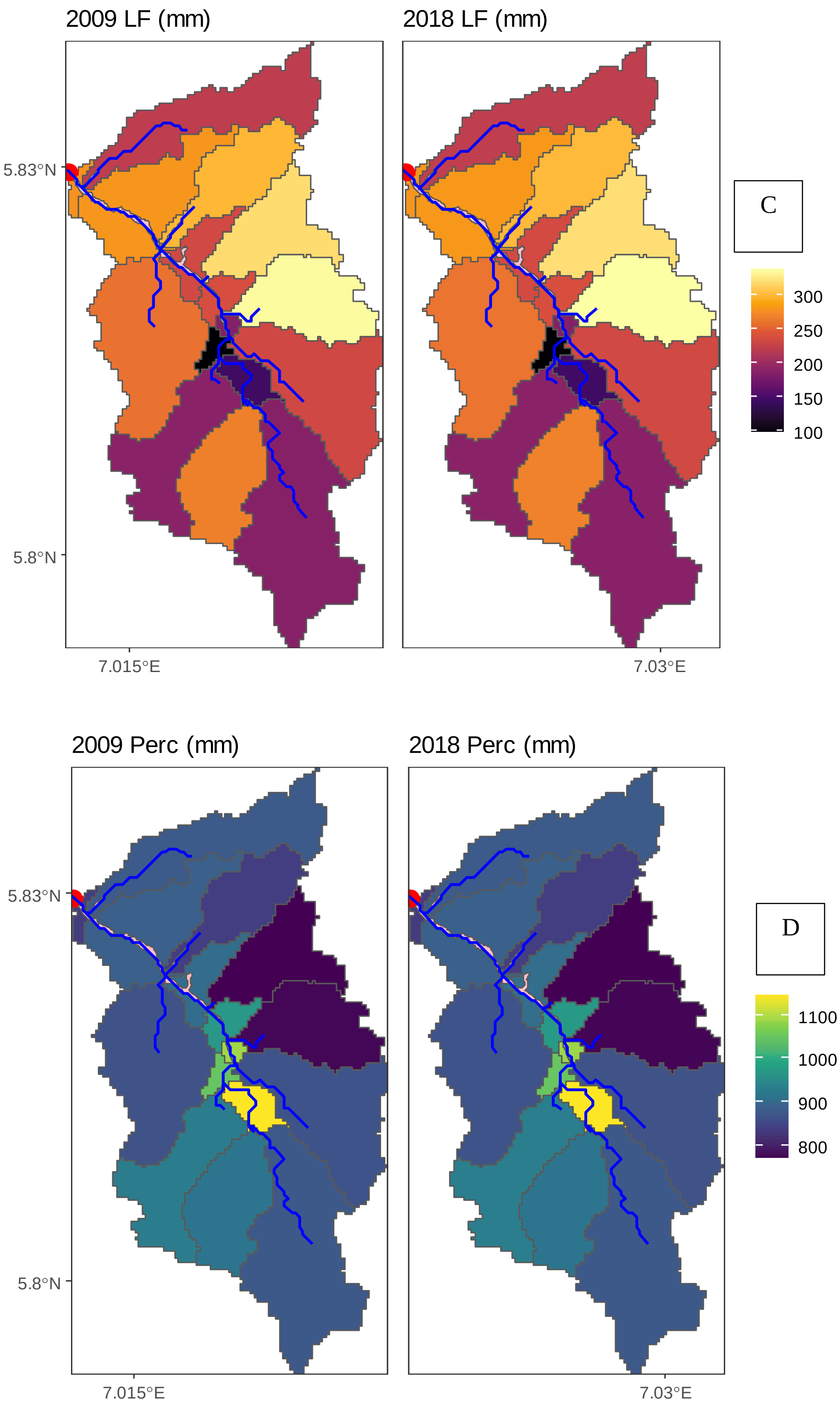

Figure 5.7 cntd: Orlu1 watershed

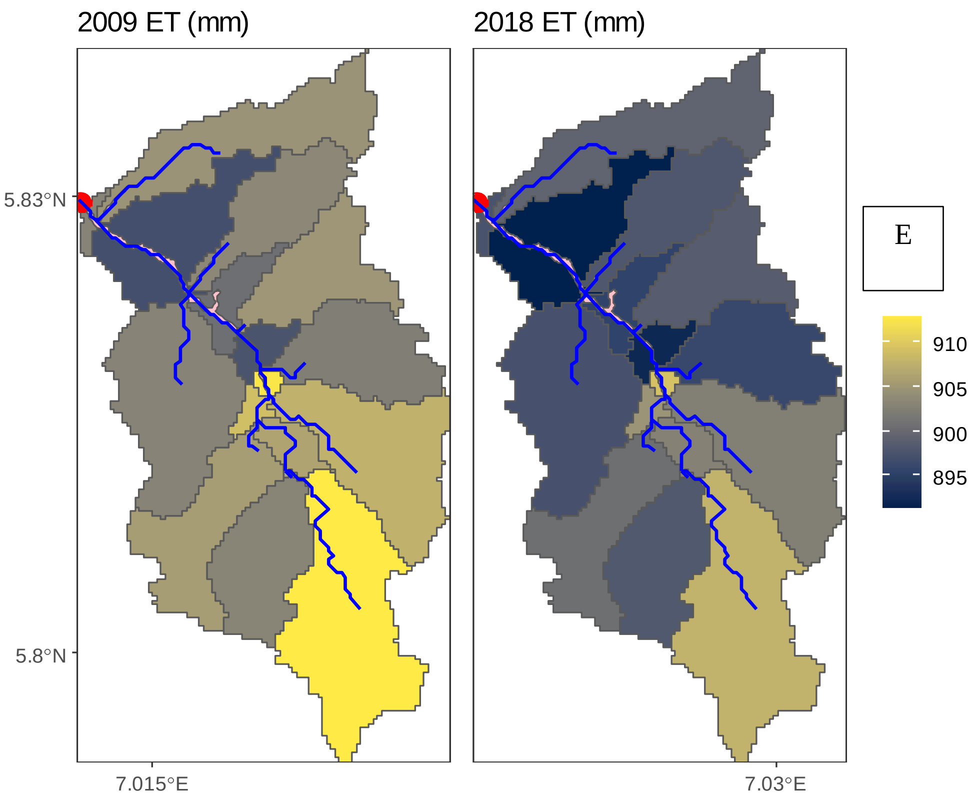

Figure 5.7 cntd: Orlu1 watershed, same land use and different rainfall totals. A, modelled streamflow. 2009 rainfall had the highest modelled streamflow volume. B, surface runoff contribution to streamflow reduced between 2009 and 2018. C, lateral flow contribution to streamflow. Minimum volumes of lateral flow remained at 99 mm for both years. D, percolation estimates. Maximum percolation values slightly reduced from between 2009 and 2018. E, evapotranspiration. Maximum loss dropped from 913 to 909 mm for 2009 and 2018 respectively. Total rainfall volumes for 2009 and 2018 were 2362 and 2351 mm respectively.

5.1.1.1 Same rainfall, different land use

Model application in different environmental settings indicate that increase in non-vegetated class results in increased surface flow contribution to streamflow. Modelled surface runoff increased with increase in non-vegetated class between 2009 and 2018 in the Amucha area (figure 5.3). For example, minimum runoff volumes were 90 mm and 201 mm while maximum runoff estimates were 308 mm and 765 mm accordingly for 2009 and 2018. There was increase in total streamflow out of the catchment from 176 m^3/s to 177 m^3/s for 2009 and 2018 land uses respectively. Lateral flow estimates are highest in sub-basin 30, same sub-basin covers most parts of the gully. There was a reduction in minimum and maximum values of lateral flow from 158 to 115 mm and 667 to 617 mm for 2009 and 2018 land-use maps respectively. There was a reduction in estimated minimum and maximum percolation values from 696 to 555 mm and 1254 to 1080 mm for 2009 and 2018 correspondingly. Minimum evapotranspiration loss reduced from 886 to 850 mm while maximum loss dropped from 907 to 904 mm for 2009 and 2018 respectively (figure 5.3). In the Orlu1 watershed, there was a reduction in total streamflow out of the catchment from 137 m^3/s to 136 m^3/s for 2009 and 2018 land uses, respectively (figure 5.5). Surface runoff contribution to streamflow increased with increase in non-vegetated class between 2009 and 2018, for example, minimum estimated runoff volumes were 166 mm and 533 mm while maximum volumes totalled 390 mm and 797 mm for 2009 and 2018 accordingly. There was a reduction in minimum and maximum values of lateral flow from 99 to 71 mm and 390 to 275 mm for 2009 and 2018 respectively. Minimum and maximum percolation values reduced from 769 to 481 mm and 1146 to 792 mm for 2009 and 2018 correspondingly. Minimum evapotranspiration loss increased from 897 to 903 mm while maximum loss rose from 913 to 921 mm for 2009 and 2018 respectively (figure 5.5).

5.1.1.2 Same land use, different rainfall totals

Regarding changes in rainfall under the same land use, although 2009 was a wetter year by 4 mm in the Amucha catchment (figure 5.6), there was a rise in total streamflow out of the catchment from 176 m^3/s to 177 m^3/s for 2009 and 2018 rainfalls, respectively. Surface runoff contribution to streamflow slightly reduced between 2009 and 2018. Minimum estimated runoff totals were 90 mm and 89 mm and maximum totals were 308 mm and 307 mm for 2009 and 2018 accordingly. Minimum volumes of lateral flow remained at 158 mm for both years while maximum values increased from 667 to 669 mm for 2009 and 2018 respectively. There was an increase in estimated minimum and maximum percolation values from 696 to 701 mm and 1254 to 1258 mm for 2009 and 2018 correspondingly. Minimum evapotranspiration loss increased from 886 to 877 mm while maximum loss dropped from 907 to 900 mm for 2009 and 2018 respectively (figure 5.6). In the Orlu1 watershed (figure 5.7), minimum streamflow remained the same at 9 m^3/s for both years, while there was a reduction in maximum flow value from 137 m^3/s to 136 m^3/s for 2009 and 2018 rainfall totals, respectively. Surface runoff contribution to streamflow reduced between 2009 and 2018. Minimum estimated runoff volumes totalled 166 mm and 158 mm and maximum volumes equalled 390 mm and 381 mm for 2009 and 2018 accordingly. Minimum volumes of lateral flow remained at 99 mm for both years while maximum values increased from 336 to 338 mm for 2009 and 2018 respectively. There was an increase in estimated minimum percolation values from 769 to 771 while maximum percolation values reduced from 1146 to 1145 mm in 2009 and 2018 correspondingly. Minimum evapotranspiration loss reduced from 897 to 891 mm while maximum loss dropped from 913 to 909 mm for 2009 and 2018 respectively.

5.1.1.3 Summary of exploratory sensitivity analysis – influence of local drivers

Increased surface flow due to higher non-vegetated surfaces does not necessarily imply higher streamflow discharge from a catchment as observed in the Orlu1 watershed (figure 5.5) where there was reduction in streamflow in 2018 despite increase in non-vegetated surfaces. There was higher contribution of lateral flow to streamflow in the Amucha catchment than in the Orlu1 catchment, (figures 5.5 and 5.6). Although the Amucha area had a higher volume of rainfall, the area also has higher sand contents than the Orlu catchment (section 4.4.1), a characteristic that will likely increase infiltration. Moreover, local slope angle was higher in Amucha than the Orlu1 area, a factor that influences lateral flow. More water was lost to deep-aquifer recharge due to lower slope angles in the Orlu1 watershed. Therefore, contribution of sub-surface flow which varied between the two catchments is the likely reason both catchments behaved differently when same amount of rainfall was used for the two years of analysis (2447 and 2362 mm for Amucha and Orlu1 respectively) in different land-use classes.

Spatial configuration of land use in individual sub-basins influence volume of surface runoff into and out of channel reaches. For example, in sub-basins with higher non-vegetated surfaces, greater runoff volumes into channel reaches were modelled, while sub-basins with higher tree-cover recorded lower contributions. Hence, if the upstream sub-basins have higher non-vegetated surfaces, there is higher surface runoff contribution to streamflow in these upstream sub-basins, however, when this surface runoff flows into downstream channels with dense vegetal cover, there is increased infiltration of surface flow in the downstream sub-basins. Modelling results indicate that these land-use dynamics reduce streamflow which likely affects gully erosion.

5.1.2 Sample results of hydrological processes from modelled catchments

In the following paragraphs, modelled results are presented for five catchments (IdNorthWS, IdeatoSouth_gully1, IdeatoSouth_gully2, IdNorthWS1, Njaba2) to illustrate effects of changes in land use on gully catchment hydrology. These catchments were chosen for two reasons: first, apart from Njaba2, the other catchments were captured in the 2014 satellite data (section 4.1.1) and thus were useful to understand response of catchment hydrology to stepwise changes in land use between 2009 and 2014, and 2014 – 2018. These changes in hydrology likely affect gully responses. Secondly, these catchments captured the variability in response of gullies to different hydrological processes (section 5.3). For example, gully expansion was recorded alongside higher: sub-surface flow, surface flows and surface and sub-surface flows in these five watersheds.

1. IdNorthWS

The gully in this catchment was found in sub-basins 8, 9, 10, 11 (Figure 5.8), sub-basin sizes are 0.03 km^2, 0.02 km^2, 0.04 km^2, and 0.15 km^2 accordingly. There was sustained reduction in tree/fallow-cover from 2009 to 2018 (Table 5.2 and figure 5.9), similarly, estimated hydrological processes responded to these changes in land use (figure 5.10). 2009 was the wettest year with rainfall of 2447 mm, followed by 2018 with 2443 mm and 2014 with 2412 mm of rain. Average temperature values for 2009 and 2018 were 27°C and 28°C in 2014. Total estimated streamflow out of sub-basin 11 was 9 m^3/s in 2009, this value remained the same in 2014 (despite reduced rainfall), and increased to 18 m^3/s in 2018, yet 2009 was wetter than 2018.

Table 5.2: IdNorthWS land-use changes

	2009	2014	2018
Non-vegetated (%)	16.8	25.7	17
Open vegetation (%)	36	51.6	70.9
Tree/fallow (%)	47.2	22.7	12.1

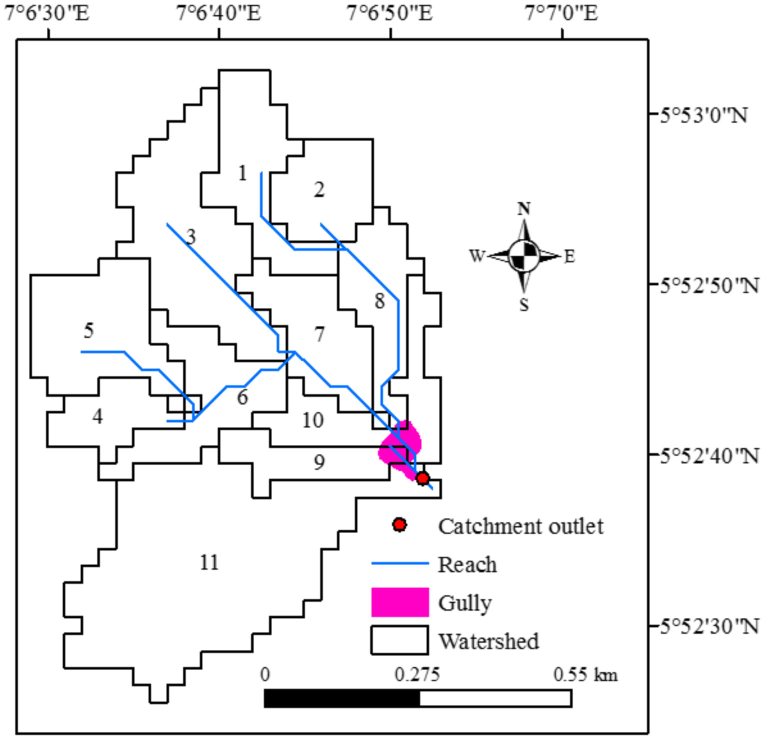

Figure 5.8: IdNorthWS gully watershed. Gully ID, 23. Gully is found in sub-basins 8, 9, 10 and 11. Modelled sub-basins are labelled.

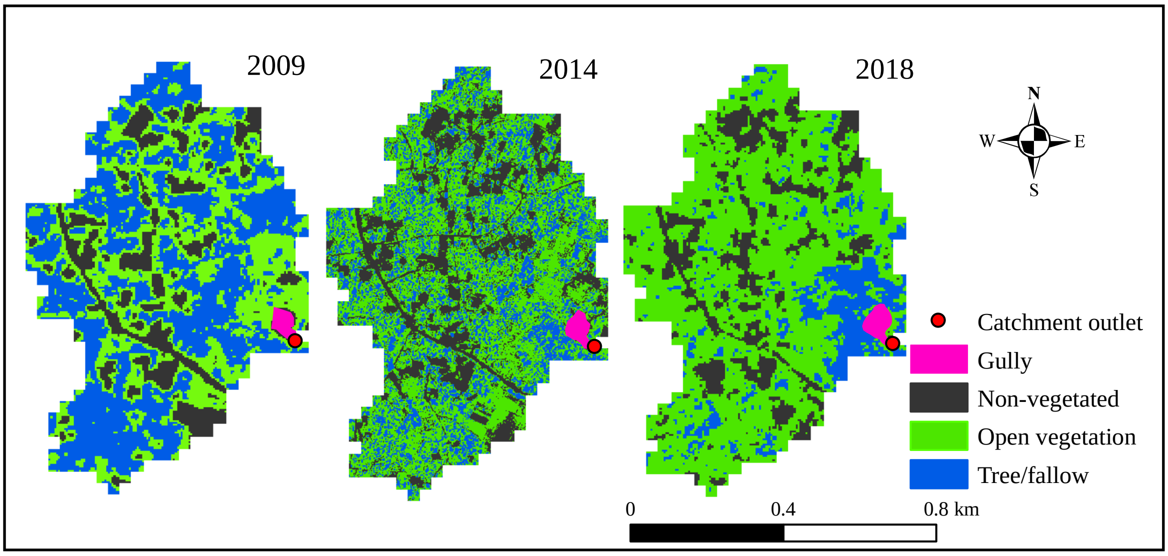

Figure 5.9: IdNorthWS land-use changes, showing sustained reductions in tree/fallow cover from 2009 to 2018. 2009, Non-vegetated = 16.8%, open vegetation = 36%, tree/fallow = 47.2%. 2014 Non-vegetated = 25.7%, open vegetation = 51.6%, tree/fallow = 22.7%. 2018 Non-vegetated = 17%, open vegetation = 70.9%, tree/fallow = 12.1%. Non-vegetated areas remained at low density from 2009 to 2018. There is higher fallow-cover near the gully in 2018. Changes in gully sizes are also visible.

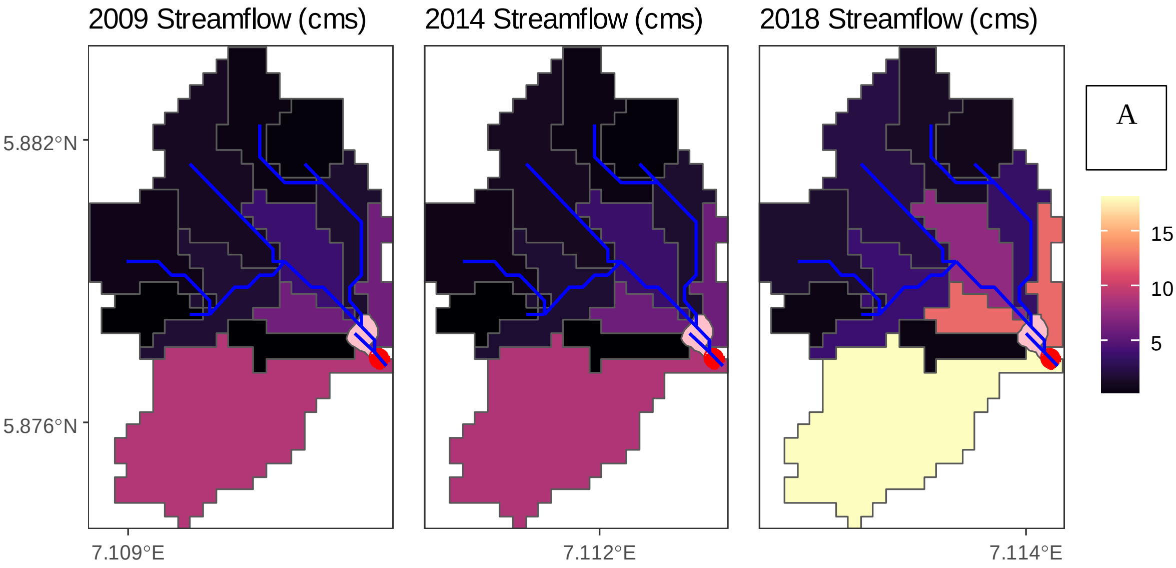

Figure 5.10: IdNorthWS hydrology.

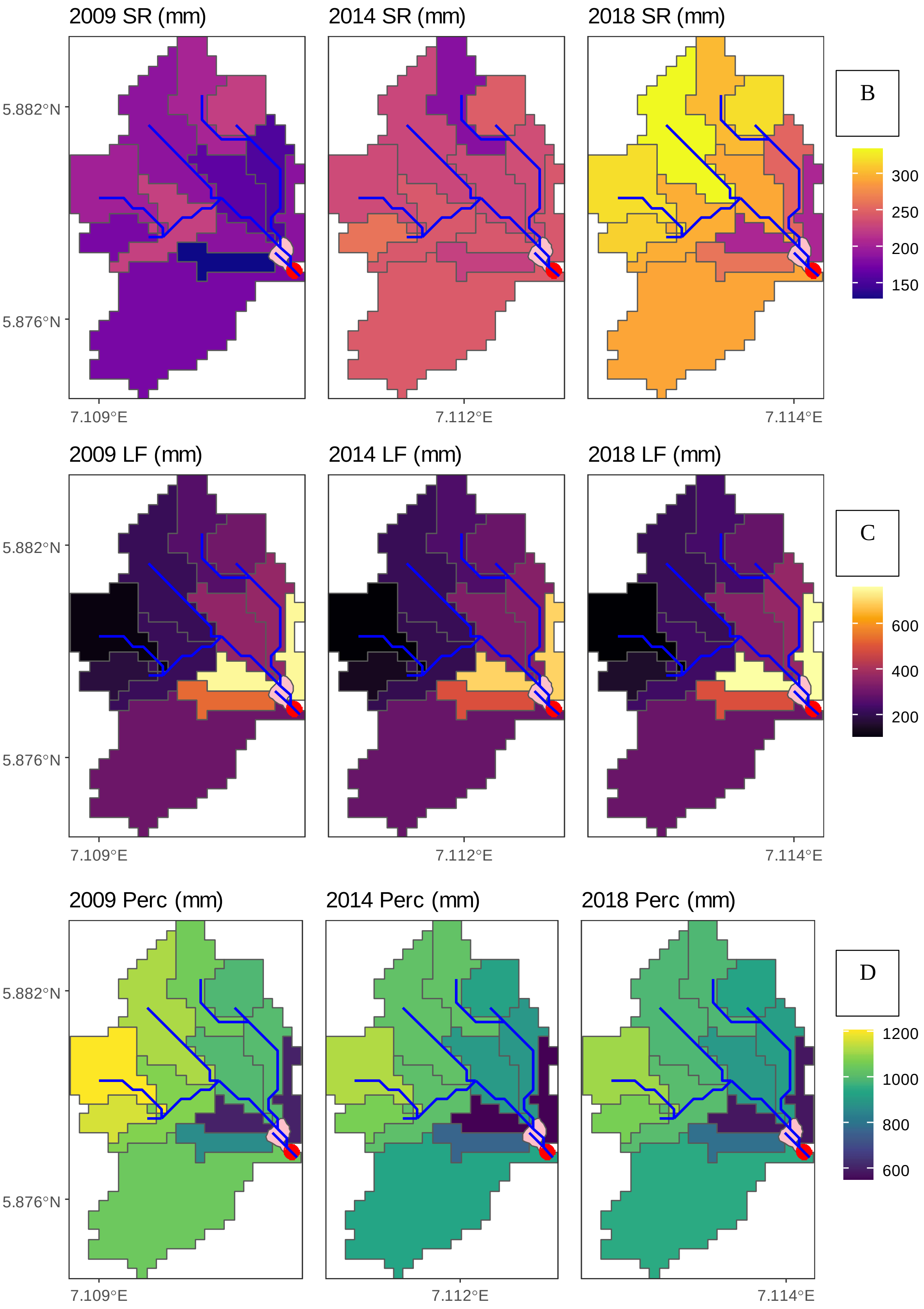

Figure 5.10 cntd: IdNorthWS hydrology.

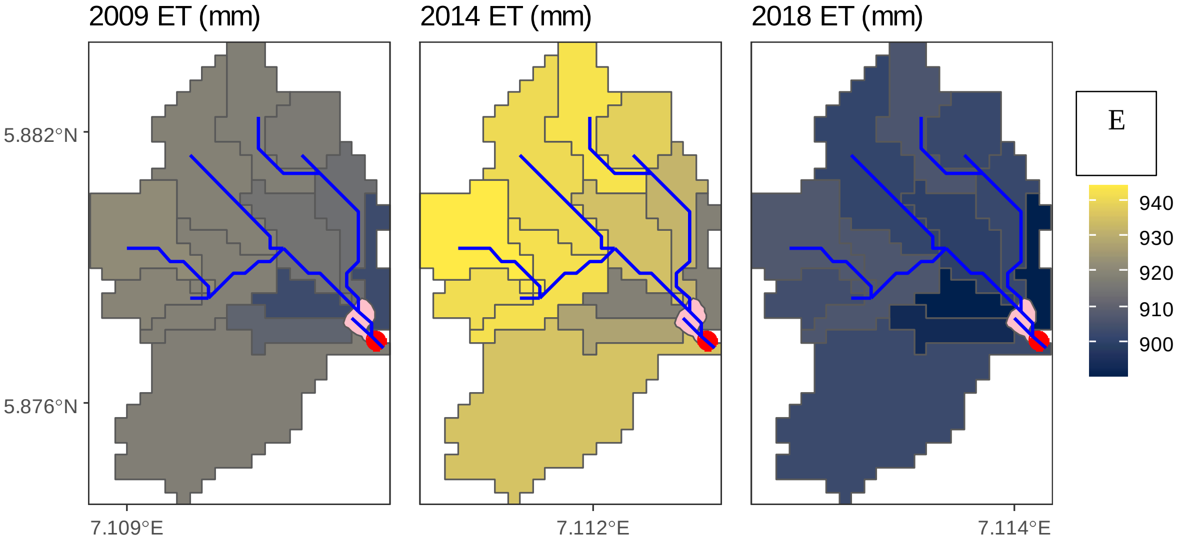

Figure 5.10 cntd: IdNorthWS hydrology, A, estimated streamflow. Total flow out of the catchment remained the same at 9 m³/s for 2009 and 2014, and increased to 18 m³/s in 2018. B, surface runoff contribution to streamflow. There was sustained increase in maximum surface runoff estimate from 226 mm in 2009 to 262 and 334 mm in 2014 and 2018 respectively. These increased values were in response to reductions in tree/fallow-cover. C, lateral flow contribution to streamflow. Maximum lateral flow estimates were observed in sub-basins 9 and 10, part of the gully in this catchment lies in both sub-basins. Maximum lateral flow was recorded in 2018 (763 mm) perhaps due to higher infiltration caused by higher fallow-cover, followed by 2009 (753 mm) and 2014 (699 mm). D, percolation estimates. Maximum percolation was recorded in 2009 (1211 mm), followed by 2014 (1130 mm) and 2018 (1112 mm). E, evapotranspiration. Maximum evapotranspiration loss was observed in 2014 (944 mm), followed by 2009 (922 mm) and 2018 (907 mm). Total annual rainfall for 2009 was 2447 mm, 2412 mm for 2014 and 2443 mm in 2018.

Estimated annual volume of surface runoff increased between 2009 and 2014 in all but one sub-basin (sub-basin 1). Sub-basin 1 experienced a reduction in open vegetation class between 2009 and 2014 (Table 5.3) while tree/fallow-cover remained the same. This situation led to the reduction in estimated volume of runoff. Open vegetation class (parameterised as cassava) has higher Curve Number than non-vegetated urban low-density class (Table 3.7). All other sub-basins had reductions in tree/fallow cover between 2009 and 2014 (Table 5.3). Increase in surface runoff was modelled in seven sub-basins between 2014 and 2018, while reductions were modelled in four sub-basins (7, 8, 9, 10). These changes in surface runoff are driven by changes in land use. With regards to lateral flow, estimated volumes of lateral flow were highest in sub-basins 9 and 10, both sub-basins cover and deliver flow into the gully directly. Also, sub-basins 9 and 10 have larger land areas under 10 – 40% slope class (Table 5.3).

Therefore, while local slope is often associated with increase in volume of surface runoff (Gómez-Gutiérrez et al. 2015), lateral flow is also influenced by local slope configuration. There were sustained reductions in lateral flow across all sub-basins between 2009 and 2014. Estimated lateral flow was higher in 2014 in sub-basins 1, 2, 5, and 9 than in 2018, while the remaining seven sub-basins had higher lateral flow volumes in 2018 compared to 2014. Reductions in fallow cover in sub-basins 1, 2 and 5 led to reductions in infiltration, while increase in open-vegetated areas in sub-basin 9 between 2014 and 2018 increased runoff. These changes in land use are likely reasons lateral flow was higher in 2014 than 2018 for these sub-basins. In the remaining seven sub-basins where lateral flow was higher in 2018, several reasons are provided: First, higher rainfall: the year 2018 was wetter than 2014 as already mentioned and thus there is more water to infiltrate and flow laterally (where the land cover is favourable). Secondly, land-use configurations: as noted, there was higher fallow-cover in some sub-basins (e.g. sub-basin 10) in 2018 than 2014 (figure 5.9). Thirdly, sub-basin sizes: a smaller percentage cover (e.g. 10%) of a particular land use in a bigger sub-basin (e.g. 0.15 km^2) has larger landmass than the higher percentage (e.g. 35%) cover in a smaller sub-basin (e.g. 0.04 km^2). Finally, the local slope configuration, which influences lateral flow in a sub-basin is important. Sustained reductions in percolation were observed from 2009 to 2018 and 2014 had the highest estimates of evapotranspiration losses due to higher temperature values.

Table 5.3: IdNorthWS sub-basins' changes in land-use, Non-veg = Non-vegetated, Open-veg = open vegetation, T/F = Tree/Fallow, SR = Surface runoff, LF = Lateral flow, Perc = Percolation. Sub-basins with higher slope angles have higher modelled lateral flow volumes.

	Size (km^2)	2009					2014				2018				Slope (%)	
		Land use		SR (mm)	LF (mm)	Perc (mm)	Land use (%)	SR (mm)	LF (mm)	Perc (mm)	Land use (%)	SR (mm)	LF (mm)	Perc (mm)		
Sub-basin1	0.04	Non-veg (%)	20.5	205.07	262.18	1060.60	27.30	185.70	252.41	1030.61	27.30	302.52	239.43	995.11	0-10	93.2
		Open-veg (%)	38.6				31.80				65.90				11-20	6.8
		T/F (%)	40.9				40.90				6.80				21-30	
															31-40	
Sub-basin2	0.03	Non-veg (%)	25.8	225.11	307.41	996.85	35.50	247.51	295.14	929.99	19.40	320.17	288.64	931.78	0-10	80.7
		Open-veg (%)	41.9				48.40				77.40				11-20	19.4
		T/F (%)	32.3				16.10				3.20				21-30	
															31-40	
Sub-basin3	0.07	Non-veg (%)	13.2	189.56	213.64	1124.22	26.30	230.98	212.38	1027.17	13.20	333.68	213.02	994.73	0-10	94.7
		Open-veg (%)	38.2				48.70				85.50				11-20	5.3
		T/F (%)	48.7				25.00				1.30				21-30	
															31-40	

Sub-basin4	0.02	Non-veg (%)	13	178.45	180.02	1168.03	30.40	261.93	134.70	1073.26	13.00	313.60	153.18	1071.75	0-10	100
		Open-veg (%)	34.8				56.50				78.30				11-20	
		T/F (%)	52.2				13.00				8.70				21-30	
															31-40	
Sub-basin5	0.05	Non-veg (%)	25.9	201.29	112.34	1210.87	33.30	233.85	104.06	1129.64	27.80	320.30	103.24	1112.05	0-10	100
		Open-veg (%)	33.3				44.40				70.40				11-20	
		T/F (%)	40.7				22.20				1.90				21-30	
															31-40	
Sub-basin6	0.04	Non-veg (%)	25.6	226.36	215.91	1085.37	39.50	244.07	203.75	1021.18	25.60	296.83	228.73	1010.91	0-10	100
		Open-veg (%)	41.9				44.20				65.10				11-20	
		T/F (%)	32.6				16.30				9.30				21-30	
															31-40	
Sub-basin7	0.04	Non-veg (%)	2.6	164.29	364.45	1002.42	18.00	233.40	334.25	908.67	7.70	293.90	344.28	904.84	0-10	71.8
		Open-veg (%)	38.5				56.40				76.90				11-20	25.6
		T/F (%)	59				25.60				15.40				21-30	2.6
															31-40	

Sub-basin 8	0.03	Non-veg (%)	0	156.04	369.12	1007.84	11.80	235.63	342.93	900.82	14.70	253.16	368.84	918.40	0-10	88.2
		Open-veg (%)	38.2				61.80				58.80				11-20	5.9
		T/F (%)	61.8				26.50				26.50				21-30	2.9
															31-40	2.9
Sub-basin 9	0.02			130.46	535.54	869.75		226.41	493.06	764.19		262.25	493.05	794.01		
		Non-veg (%)	8.7				21.70				4.40				0-10	47.8
		Open-veg (%)	26.1				52.20				69.60				11-20	39.1
		T/F (%)	65.2				26.10				26.10				21-30	8.7
															31-40	4.4
Sub-basin 10	0.04			187.76	752.75	602.82		243.08	698.82	550.14		207.49	762.88	582.23		
		Non-veg (%)	18.4				26.30				2.60				0-10	34.2
		Open-veg (%)	42.1				57.90				57.90				11-20	52.6
		T/F (%)	39.5				15.80				39.50				21-30	13.2
															31-40	0
Sub-basin 11	0.15	Non-veg (%)	18.9	178.03	299.94	1049.84	21.40	245.52	291.82	938.23	18.20	292.28	294.32	953.22	0-10	83

		Open-veg (%)	31.5				57.90				69.20				11-20	14.5
		T/F (%)	49.7				20.80				12.60				21-30	1.3
															31-40	1.3

2. IdeatoSouth_gully1

Two gullies, 1 and 2, were found in adjacent catchments, IdeatoSouth_gully1 and IdeatoSouth_gully2 (figure 5.11). Gully1 was visible in the 2009 satellite data but appeared to have been sand-filled sometime after 2009 as the 2014 image captured a flat surface of red-earth on the same site where gully1 was identified in 2009. However, in 2018, gully1 could be seen again. Gully2 on the other hand was not visible in the 2009 imagery and seemed to have formed post-2009 satellite data acquisition, the gully was first captured in the 2014 imagery.

Sustained reduction in tree/fallow cover was observed across the IdeatoSouth_gully1 catchment from 2009 (29%) to 2018 (0%), in the same period, non-vegetated areas rose from 25% to 59% respectively (figure 5.12). Estimated total streamflow out of gully catchment was 4.4 m^3/s in 2009, and slightly dropped to 4.3 m^3/s in 2014 and rose again to 4.4 m^3/s in 2018 (figure 5.13). Total rainfall was 2447, 2412 and 2443 mm in 2009, 2014 and 2018 respectively.

In response to reductions in fallow, surface runoff estimates were higher across all sub-basins in 2014 compared to 2009, lateral flow and percolation volumes reduced during same period due likely to reduction in infiltration brought about by reduced fallow-cover. Modelled Evapotranspiration was highest in 2014 due to higher temperature for 2014. Total surface runoff estimates were higher in 2018 than in 2014 (figure 5.13), due to the complete disappearance of fallow and increase in non-vegetated surfaces. Lateral flow was higher in 2018 than 2014, perhaps due to higher rainfall in 2018, however, total volume of estimated percolation in 2014 was greater than the 2018 estimate. Thus, while more water was available for infiltration in 2018, shallow and deep aquifer recharge were higher in 2014 than 2018. This result is significant regarding gully-driving processes, for example, where gully expansion is dominated by groundwater-driven mass movement (Okagbue & Uma, 1987), higher groundwater flow will possibly increase gully retreat. In areas where lateral flow influences gully erosion (Berry, 1970), higher lateral volume will potentially enhance gully retreat. Detailed discussions are provided in sections 5.3 and 5.4.

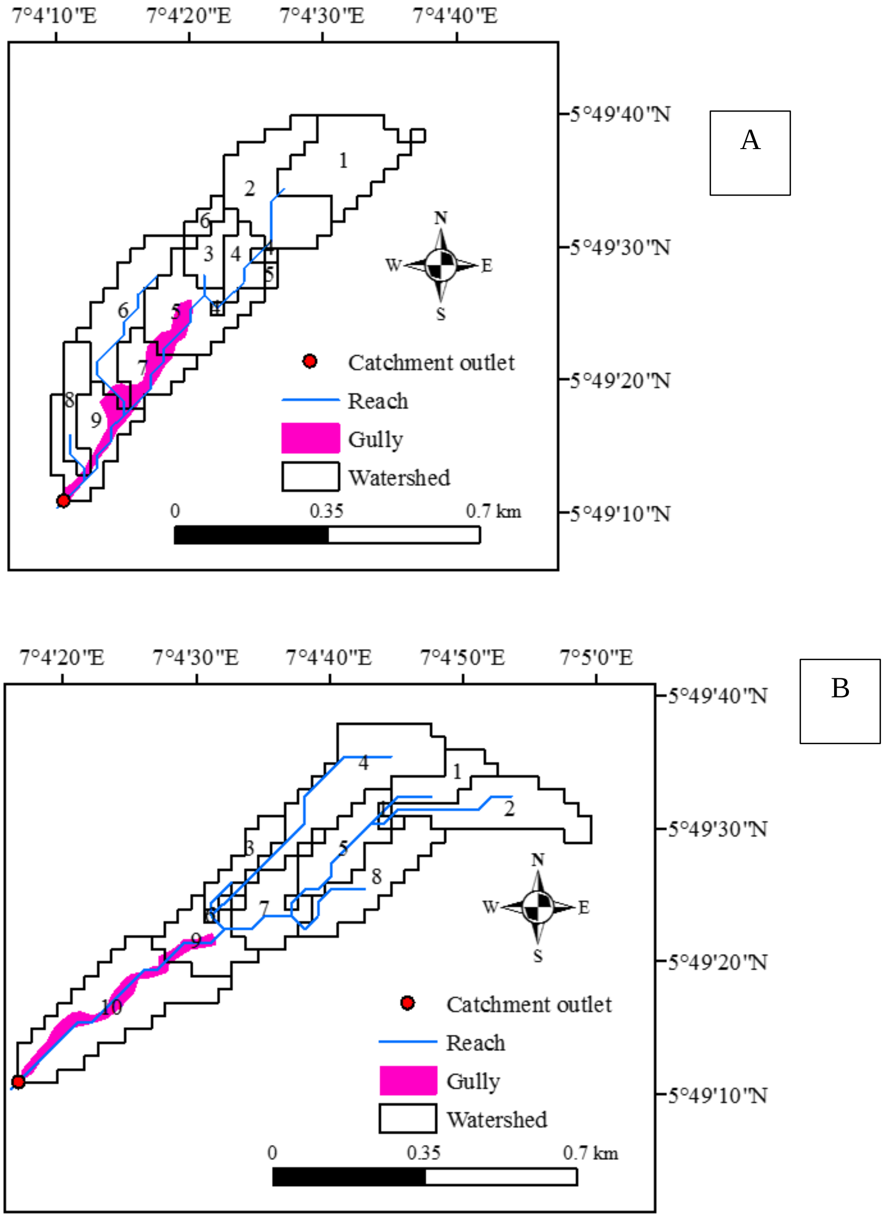

Figure 5.11: IdeatoSouth_gully1 watershed. Gully ID, 26. B, IdeatoSouth_gully2 watershed. Gully ID, 36. Modelled sub-basins are labelled.

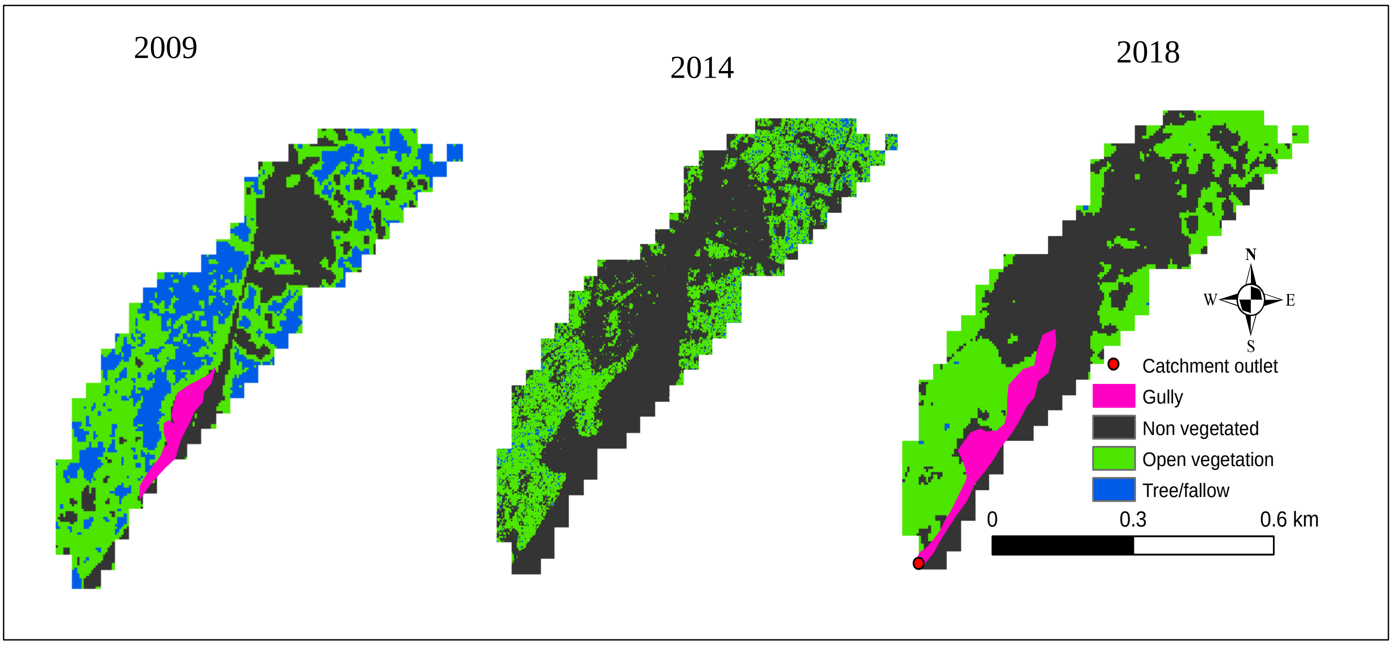

Figure 5.12: IdeatoSouth_gully1 land-use changes. 2009 non-vegetated area = 25.5%, open vegetation = 45.4%, tree/fallow = 29.2%. 2014 non-vegetated area = 57.9%, open vegetation = 38%, tree/fallow = 4.1%. 2018 non-vegetated area = 59%, open vegetation = 41%, tree/fallow = 0%. Non-vegetated class changed from low to medium density between 2009 and 2014 and remained at medium density in 2018. No gully was found in 2014 as explained in text.

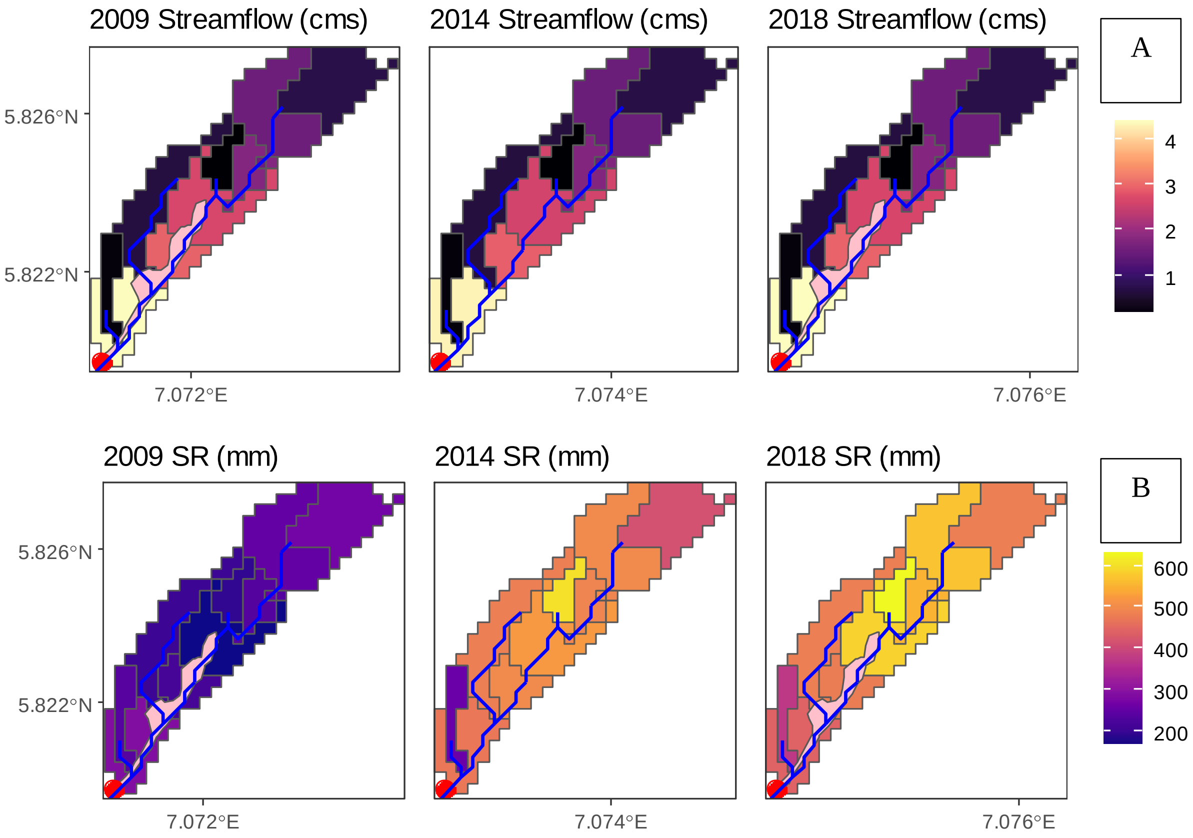

Figure 5.13: IdeatoSouth_gully1 hydrology.

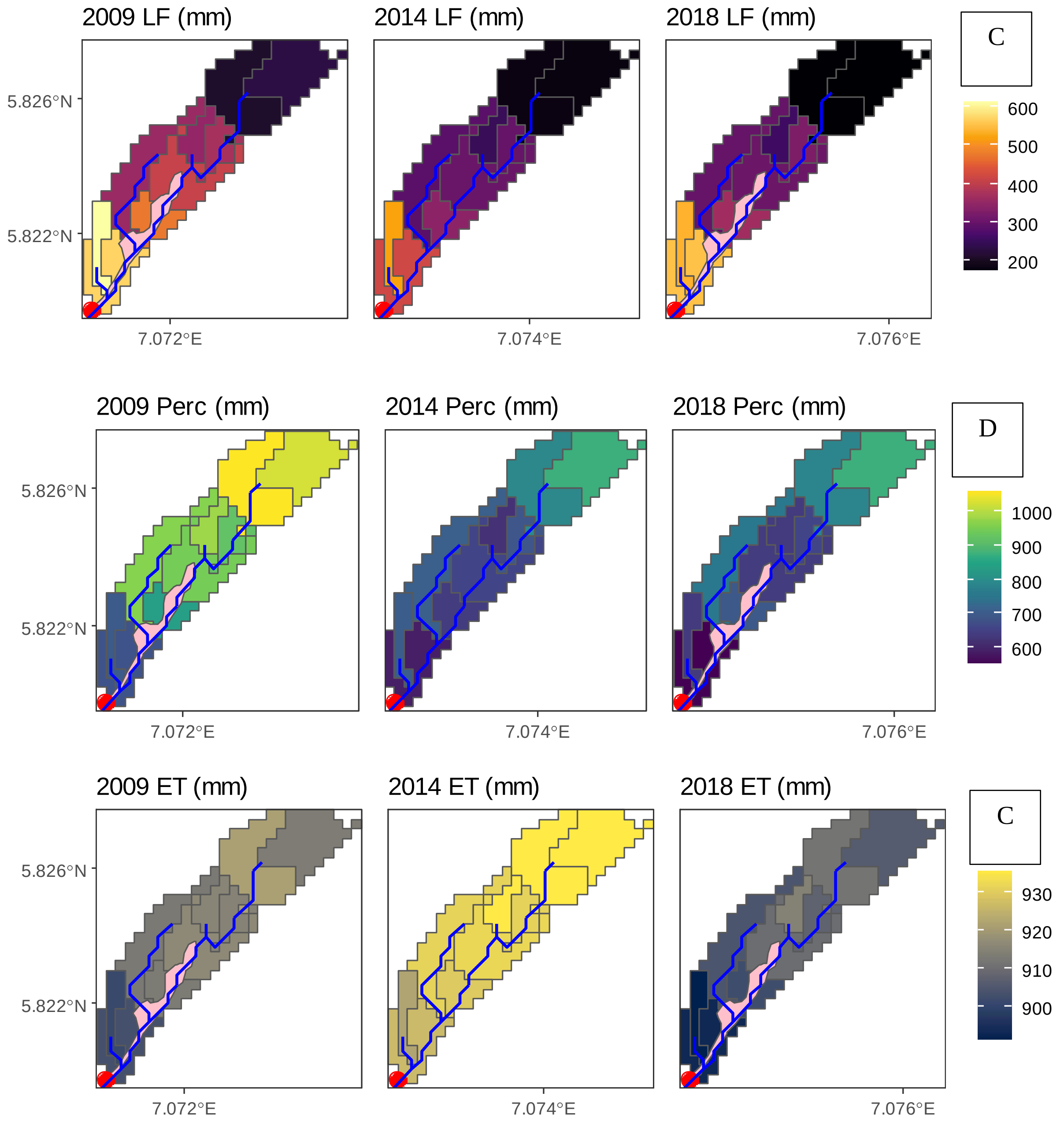

Figure 5.13 cntd: IdeatoSouth_gully1 hydrology, A, estimated streamflow. Total flow out of the catchment was 4.4, 4.3 and 4.4 m^3/s in 2009, 2014 and 2018 respectively. B, surface runoff contribution to streamflow. There was sustained increase in maximum surface runoff estimate from 170 mm in 2009 to 262 and 376 mm in 2014 and 2018 respectively. These increased values were in response to reductions in tree/fallow-cover and increased non-vegetated surfaces. C, lateral flow contribution to streamflow. Maximum lateral flow was recorded in 2009 (612 mm) followed by 2018 (553 mm) and 2014 (523 mm). D, percolation estimates. Maximum percolation was recorded in 2009 (1061 mm) due to higher vegetal cover and higher generated rainfall in same year. E, evapotranspiration. 2014 has the highest evapotranspiration value (936 mm) due to higher temperature. Total annual rainfall for 2009 was 2447 mm, 2412 mm for 2014 and 2443 mm in 2018.

3. IdeatoSouth_gully2

IdeatoSouth_gully2 covers a land area of 0.31 km^2. The non-vegetated class increased from 8.2% in 2009 to 33.4% in 2014 and dropped to 28.9% in 2018. There was change in non-vegetated class from low-density in 2009 to medium density in 2014 and 2018. Open vegetation covered 54.4% of land area in 2009 and dropped to 50.8% in 2014 but increased to 70.8% in 2018. Sustained reduction in tree/fallow was observed from 37.4% of land in 2009 to 15.8% and 0.3% in 2014 and 2018 accordingly (figure 5.14).

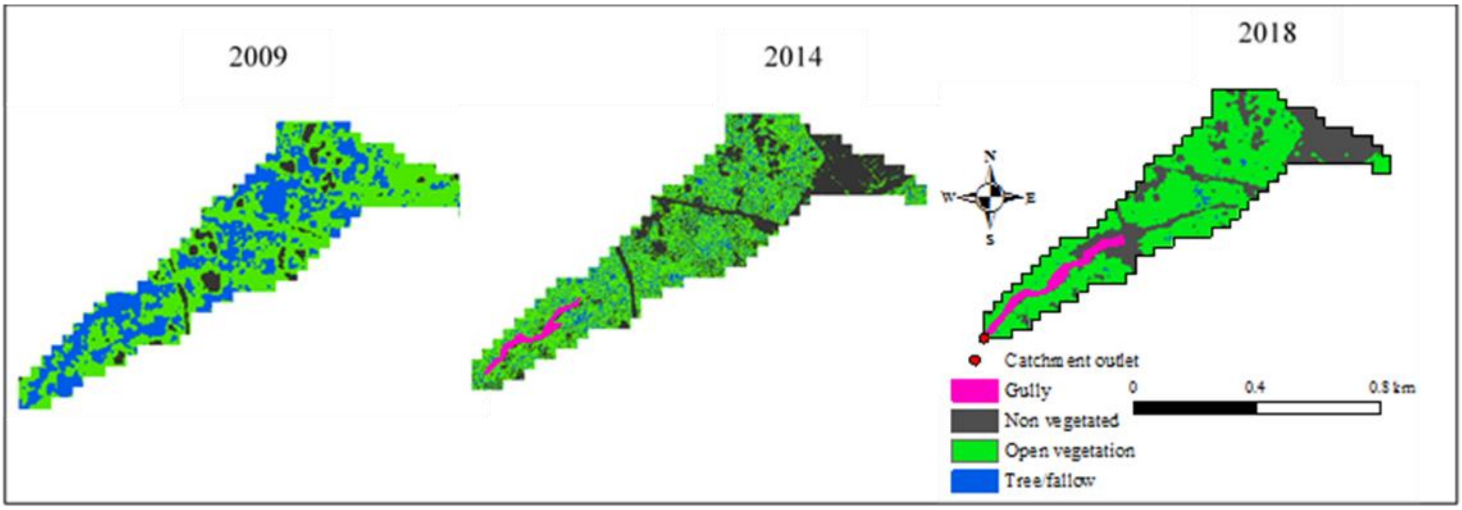

Figure 5.14: IdeatoSouth_gully2 land-use changes. 2009 non vegetated area = 8.2%, open vegetation = 54.4%, tree/fallow = 37.4%. 2014 non vegetated area = 33.4%, open vegetation = 50.8%, tree/fallow = 15.8%. 2018 non vegetated area = 28.9%, open vegetation = 70.8%, tree/fallow = 0.3%. Non-vegetated changed from low to medium density between 2009 and 2014 and remained same in 2018. No gully was found in 2009. Change in gully sizes also visible.

Total annual streamflow was 5.3 m^3/s in 2009, but slightly reduced to 5.2 m^3/s in 2014 and increased to 5.4 m^3/s in 2018 (figure 5.15). With regards to daily rainfall and streamflow events, among the three years, 2014 had the highest single daily rainfall (65.7 mm) which occurred on the 274th day of the year. The same day produced the highest single daily streamflow out of the catchment (0.15 m^3/s, figure 5.15). Maximum surface runoff volume increased from 352 mm in 2009 to 606 and 637 mm in 2014 and 2018 respectively (figure 5.15). Maximum lateral flow contribution to streamflow dropped from 497 mm in 2009 to 399 mm in 2014 and increased to 493 mm in 2018. Maximum percolation value was highest in 2009 (1161 mm). Increase in lateral flow and percolation estimates between 2014 and 2018 is likely due to availability of more rainfall in 2018 as well as reduction in non-vegetated surfaces in 2018. Evapotranspiration losses were highest in 2014 with a maximum estimate of 940 mm, followed by 2009 (918 mm) and 2018 (916 mm). Maximum temperature was recorded in 2014.

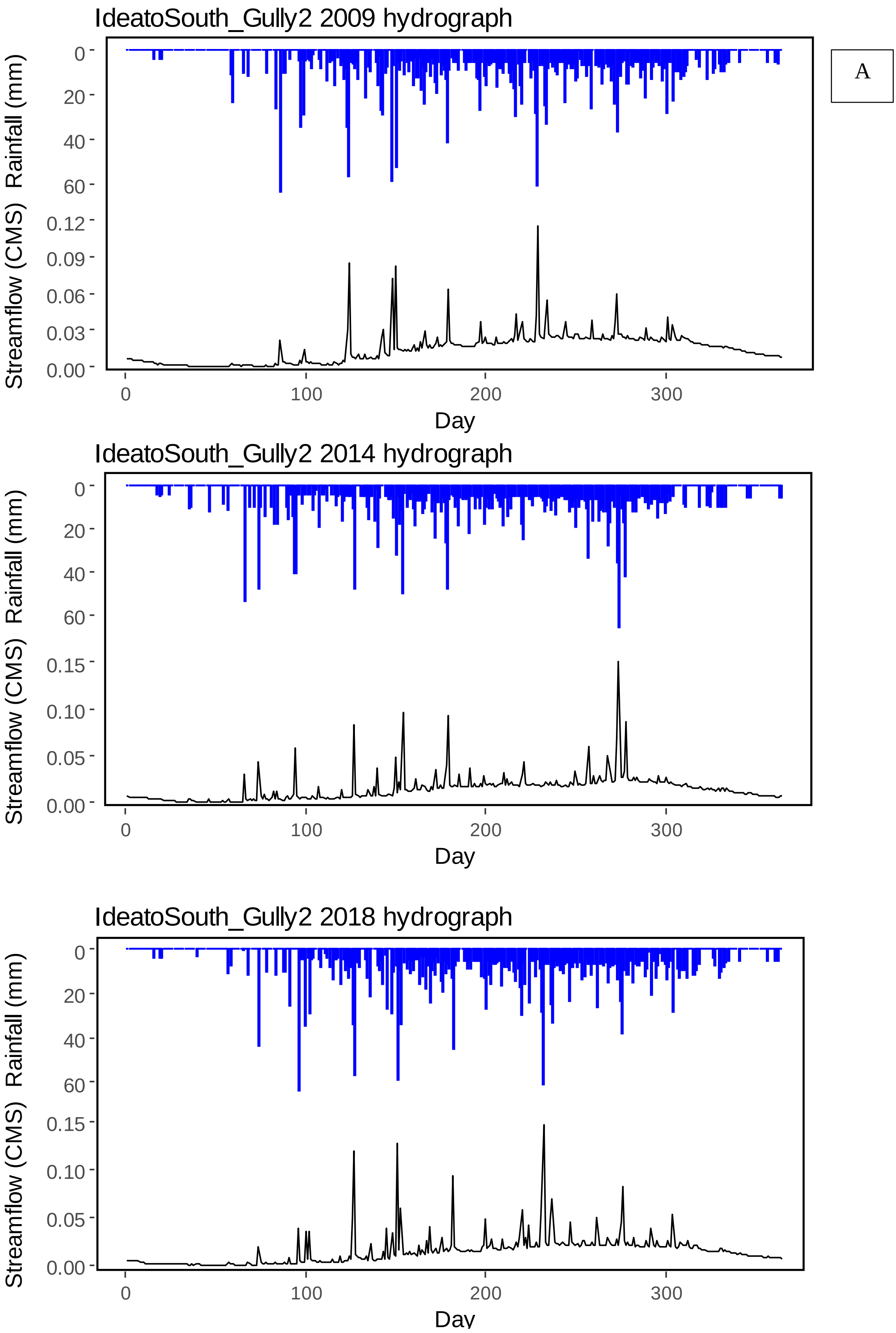

Figure 5.15: IdeatoSouth_gully2 hydrology.

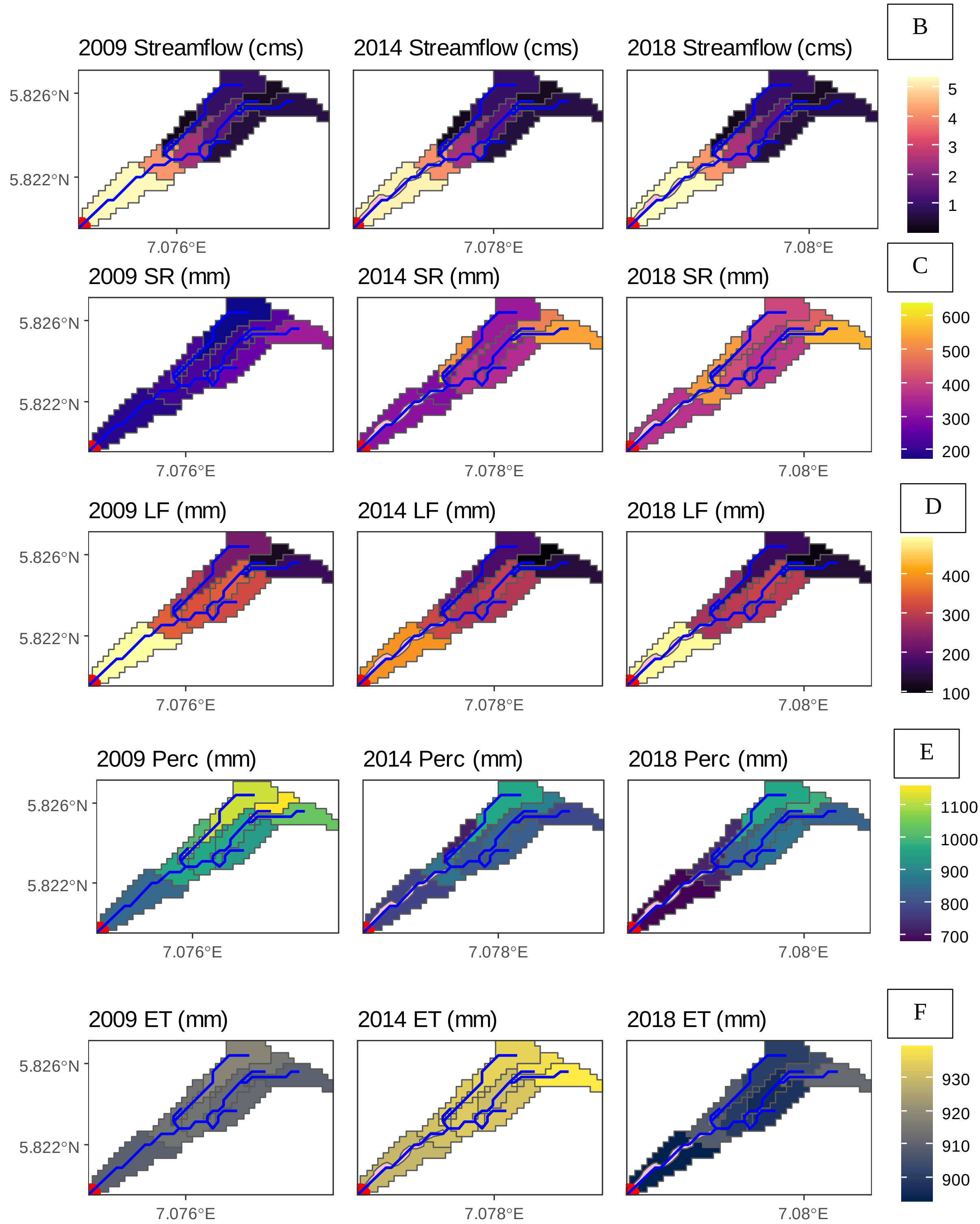

Figure 5.15 cntd: IdeatoSouth_gully2 hydrology, A, daily streamflow. 2014 had the highest single daily modelled streamflow. B, annual streamflow. Total flow out of the catchment was 5.3, 5.2, and 5.4 m^3/s in 2009, 2014 and 2018 respectively. C, yearly surface runoff contribution to streamflow. There was sustained increase in maximum surface runoff estimate from 352 mm in 2009 to 606 and 637 mm in 2014 and 2018 respectively. These increased values were in response to changes in land use. D, annual lateral flow contribution to streamflow. Maximum lateral flow was recorded in 2009 (497 mm) followed by 2018 (493 mm) and 2014 (399 mm). E, yearly percolation estimates. Maximum percolation was recorded in 2009 (1161 mm) due to higher vegetal cover and higher rainfall in same year and followed by 2018 (988 mm) and 2014 (967 mm). F, annual evapotranspiration. The year 2014 has the highest evapotranspiration value (940 mm) due to higher temperature. Annual rainfall for 2009 was 2447 mm, 2412 mm for 2014 and 2443 mm in 2018.

4. IdSouth WS1

The IdSouthWS1 catchment (figure 5.16) covers 0.08 km^2 (Table 5.1). Continuous increase in tree/fallow was recorded in the IdSouthWS1 catchment from 8.5% in 2009 to 28.1% and 36.6% in 2014 and 2018 accordingly. Non-vegetated surfaces covered 19.5%, 37.8% and 2.4% in 2009, 2014 and 2018 respectively. Open vegetation cover was 72% of land area in 2009 but reduced to 37.8% in 2014 and increased to 61% in 2018 (figure 5.16).

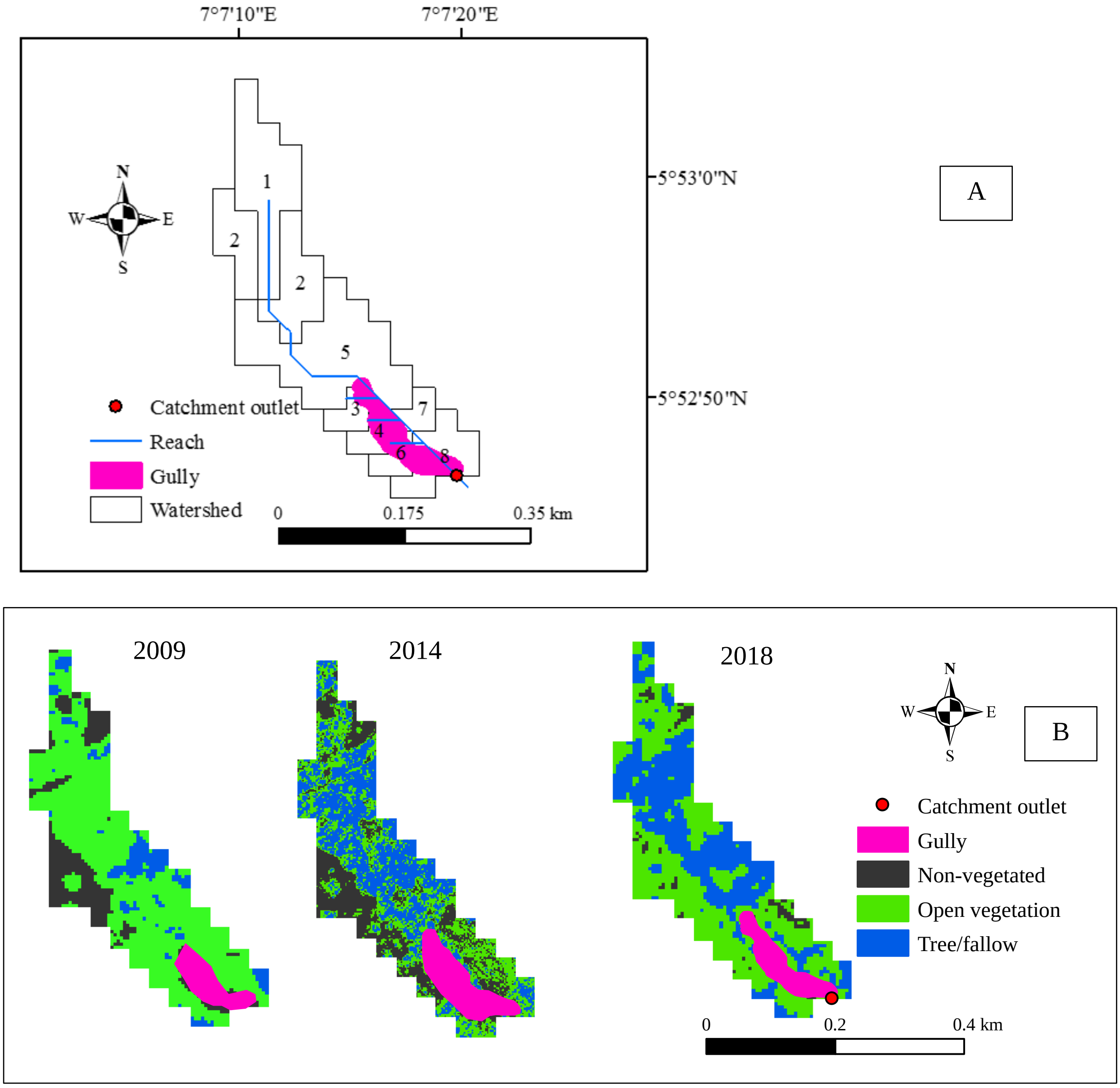

Figure 5.16: A, IdSouthWS1 gully watershed. Gully ID, 22. B, Land-use changes. There is sustained increase in tree/fallow from 2009 to 2018. Non-vegetated surfaces remained at low-density between 2009 and 2018.

Highest daily streamflow was recorded in 2011 (figure 5.17A). Total annual streamflow was 1.4, 1.3 and 1.4 m^3/s in 2009, 2014 and 2018 respectively (figure 5.17B). Total surface runoff volume was lower in 2014 compared to 2009 but was higher in 2018 in six of the eight sub-basins 2018 (1, 3, 4, 6, 7, 8). Sub-basins 2 and 5 recorded reductions in surface runoff in 2018 relative to 2014. Five sub-basins (2, 5, 6, 7, 8) recorded reductions in lateral flow while an increase was observed in the other three sub-basins (1, 3, 4) in 2014 compared to 2009. Between 2018 and 2014, there were reductions in lateral flow in four sub-basins (3, 4, 6, 8) and increase in the other four sub-basins (1, 2, 5, 7). Maximum value of percolation was highest in 2014 (928 mm) followed by 2018 (860 mm) and 2009 (854 mm) (figure 5.17). Concerning evapotranspiration, 2014 had the highest estimated value (946 mm) due to higher temperature while 2018 recorded least maximum evapotranspiration loss (903 mm). These changes in modelled hydrological processes can be related to changes in land use across sub-basins, for example, there was increase in tree/forest cover in the two sub-basins (2, 5) that experienced reductions in surface runoff in 2018 comparative to 2014 (Table 5.4). In sub-basin 2, tree/fallow cover increased from 35.3% to 58.8% and in sub-basin 5, tree-covered areas grew from 22.2% to 40.7%.

Modelling results presented so far have been for the years 2009, 2014 and 2018, very high-resolution satellite imageries were available for these years and aided gully delineation. As gully evolution is a continuous process, influence of hydrological processes during intermediate years on gullying is recognised (figure 5.17A). Modelling results show that 2011 had the highest rainfall event (125 mm) and subsequently produced highest daily streamflow while 2016 produced the least daily streamflow due to lowest rainfall event. A continuous increase in fallowed areas was observed in this catchment between 2009 and 2018, section 5.1.1 shows that higher fallow-cover reduces surface flow. Although high-resolution satellite data (similar to those used in this study) are not available for intermediate years, judging from section 5.1.1 and figure 5.16, it is suggestive that surface runoff will reduce following higher fallow-cover, however, figure 5.17 shows higher surface flow for 2011, 2012 and 2018 relative to 2014. Two reasons are provided for this observation: First, 2011, 2012 and 2018 have higher rainfalls than 2014. Secondly, while higher fallow-cover was observed for the entire catchment, sub-basin 8 whose data are presented in figure 5.17B had increased open-vegetated surfaces between 2014 and 2018, while fallow-cover remained the same (Table 5.4).

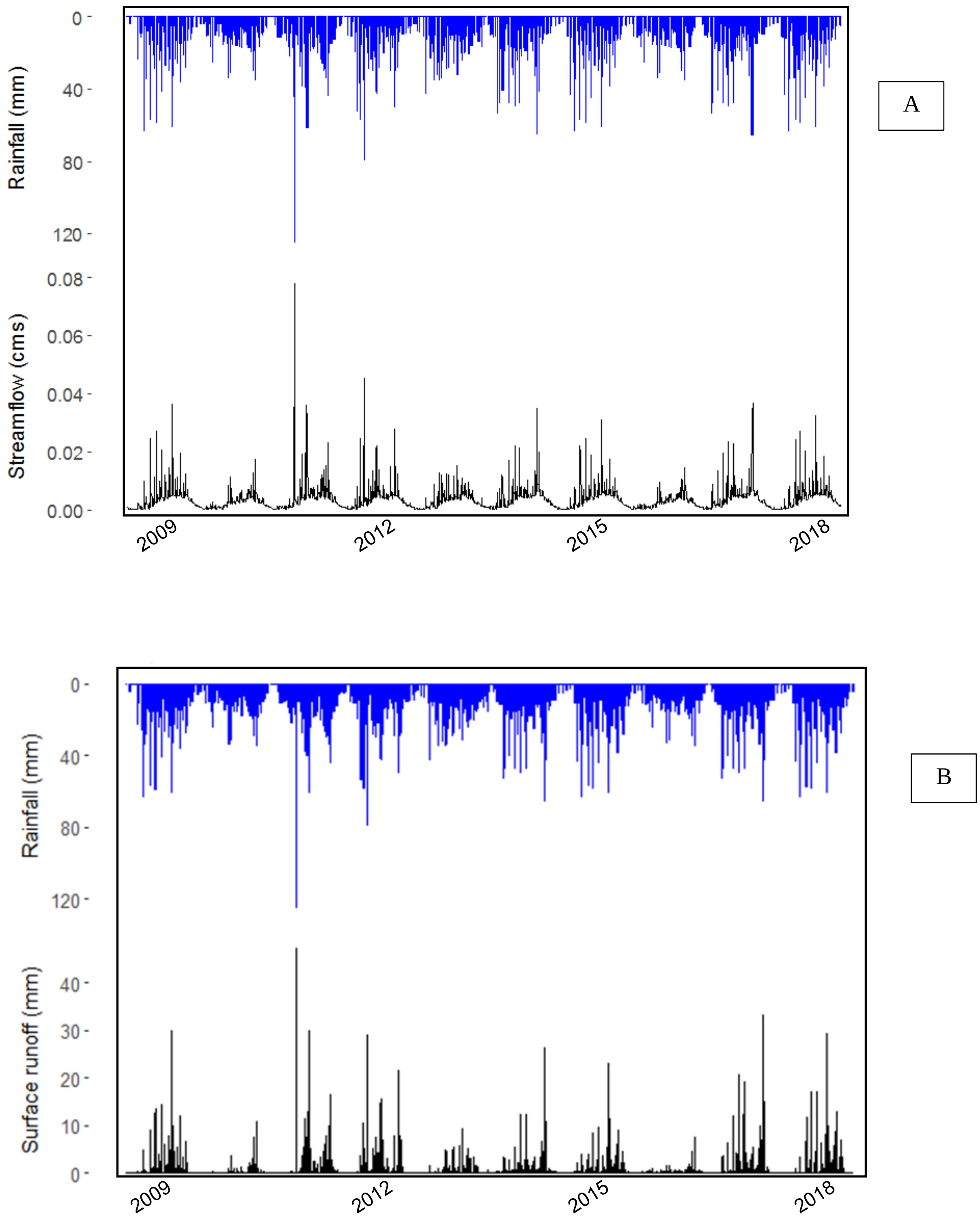

Figure 5.17: IdSouthWS1 hydrology, A, daily modelled streamflow from 2009 to 2018. Highest single daily streamflow was identified in 2011. B. Subasin8 Daily runoff.

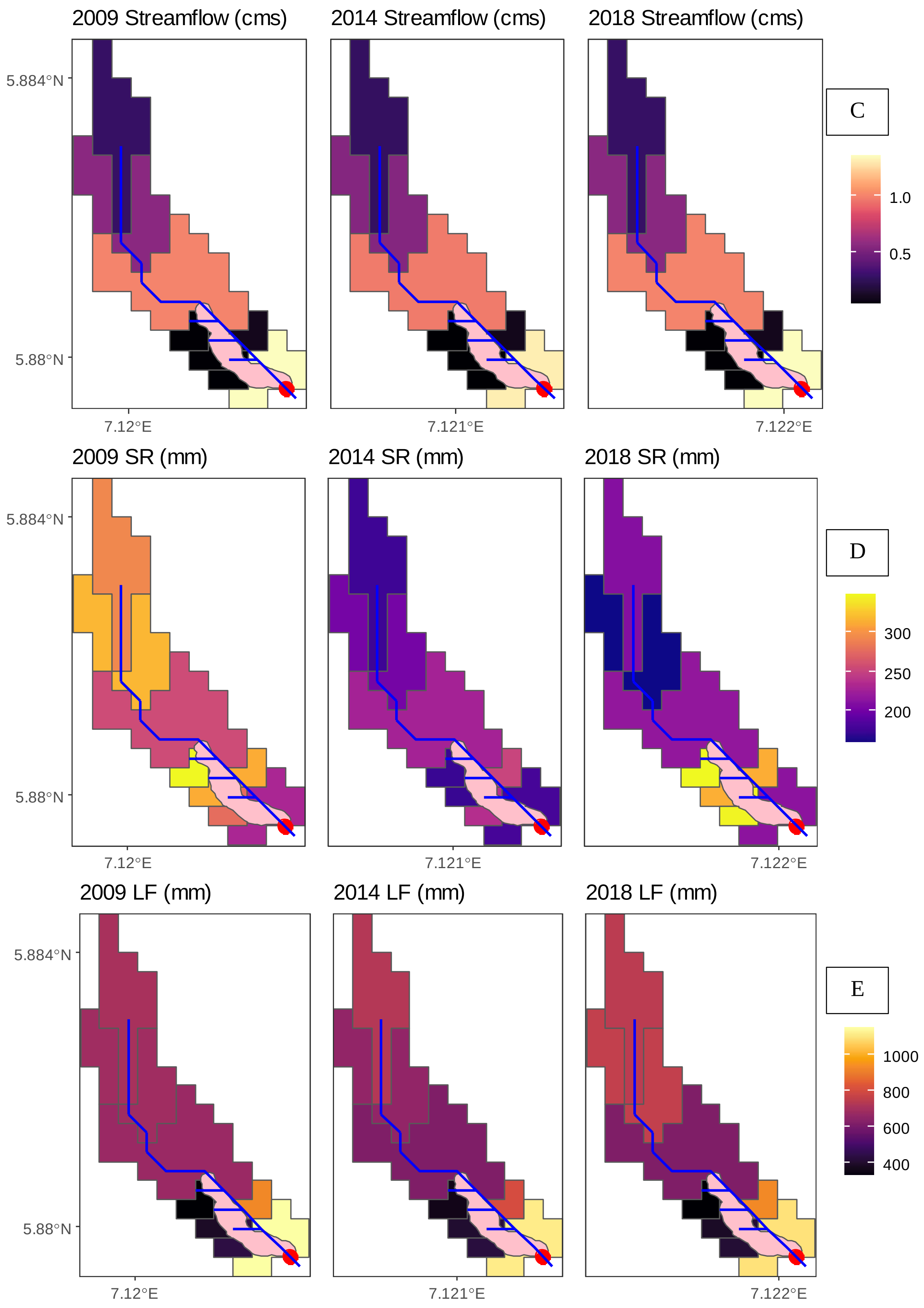

Figure 5.17 cntd.

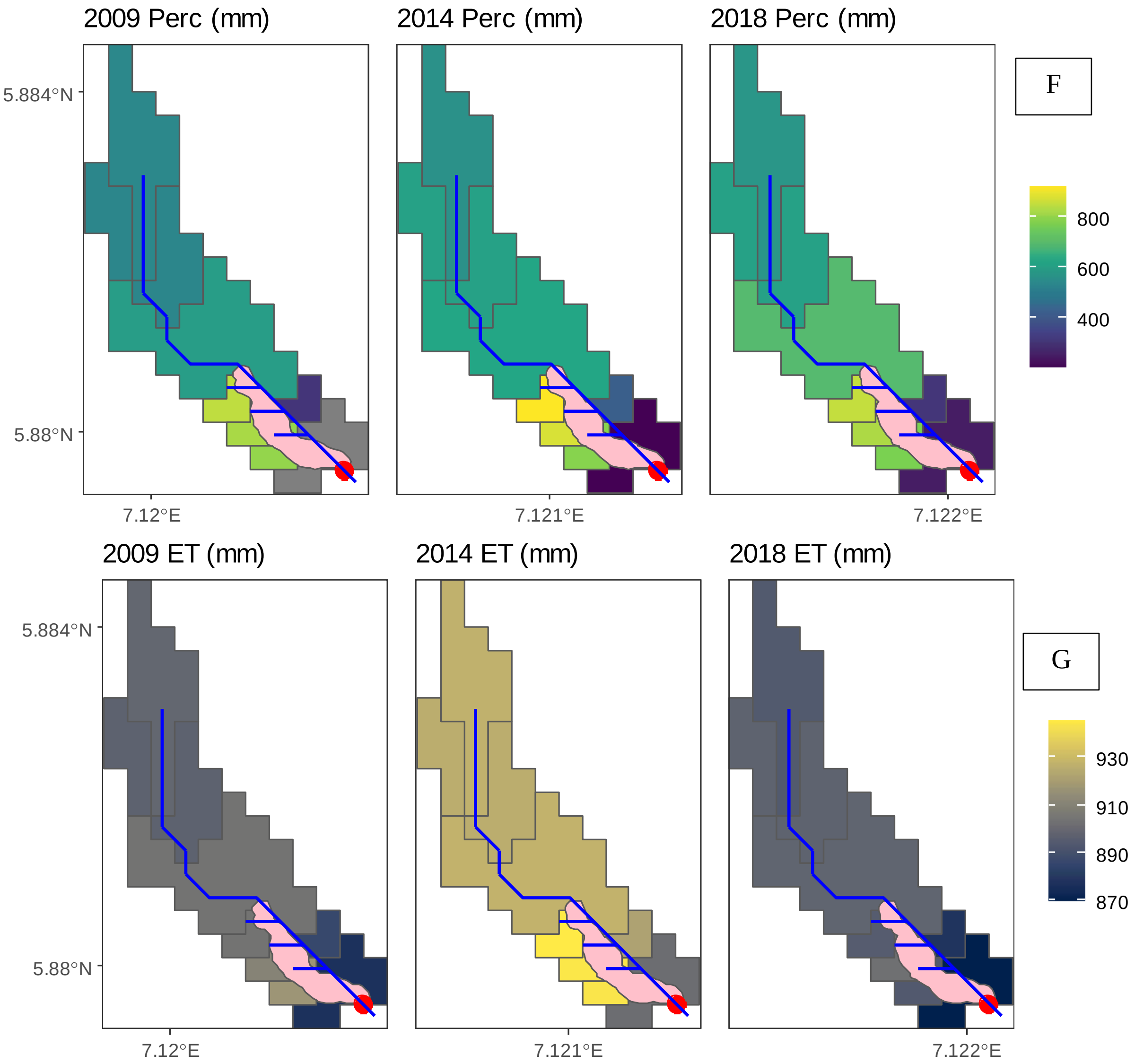

Figure 5.17 cntd: IdSouthWS1 hydrology, A, daily modelled streamflow from 2009 to 2018. Highest single daily streamflow was identified in 2011. B. Subasin8 Daily runoff. C. Total streamflow for 2009, 2014 and 2018. Total streamflow out of the catchment was 1.4, 1.3 and 1.4 m^3/s in 2009, 2014 and 2018. D, annual surface. Surface runoff reduced in 2014 in all sub-basins but increased in six of the eight sub-basins between in 2018 in response to land-use changes. E, yearly lateral flow contribution to streamflow. There was increase in lateral flow in three sub-basins (1, 3, 4) in 2014. F, yearly percolation estimates. Maximum value of percolation was highest in 2014 (928 mm). G, annual evapotranspiration. 2014 had the highest estimated value (946 mm). Total annual rainfall for 2009 was 2447 mm, 2412 mm for 2014 and 2443 mm in 2018.

Table 5.4: IdSouthWS1 sub-basins' changes in land-use, Non-veg = Non-vegetated, Open veg = open vegetation, T/F = Tree/Fallow. SR = Surface runoff, LF = Lateral flow, Perc = Percolation. Sub-basins with higher slopes have higher estimates of lateral flow.

	Size (km^2)	2009					2014				2018				Slope (%)	
		Land use (%)		SR (mm)	LR (mm)	Perc (mm)	Land use (%)	SR (mm)	LR (mm)	Perc (mm)	Land use (%)	SR (mm)	LR (mm)	Perc (mm)		
Sub-basin1	0.01	Non-veg (%)	17.70	294.69	709.47	543.11	29.40	176.91	734.81	571.27	0.00	211.25	751.39	586.14	0-10	35.3
		Open-veg (%)	76.50				29.40				58.80				11-20	64.7
		T/F (%)	5.90				41.20				41.20				21-30	
															31-40	
Sub-basin2	0.01	Non-veg (%)	11.80	319.35	690.95	538.96	17.70	203.85	661.82	619.07	0.00	160.99	766.33	617.96	0-10	41.2
		Open-veg (%)	88.20				47.10				41.20				11-20	58.8
		T/F (%)	0.00				35.30				58.80				21-30	
															31-40	
Sub-basin3	0.003	Non-veg (%)	0.00	349.23	337.85	854.61	66.70	174.34	363.43	927.52	0.00	349.88	338.07	860.01	0-10	100
		Open-veg (%)	100.00				0.00				100.00				11-20	
		T/F (%)	0.00				33.30				0.00				21-30	
															31-40	

Sub-basin4	0.003	Non-veg (%)	33.30	314.84	391.10	829.83	66.70	174.20	408.69	883.49	33.30	316.15	390.27	833.76	0-10	66.7
		Open-veg (%)	66.70				0.00				66.70				11-20	33.3
		T/F (%)	0.00				33.30				0.00				21-30	
															31-40	
Sub-basin5	0.03	Non-veg (%)	22.20	257.63	678.47	606.47	33.30	228.90	620.91	632.85	3.70	218.17	622.23	704.57	0-10	33.3
		Open-veg (%)	59.30				44.40				55.60				11-20	66.7
		T/F (%)	18.50				22.20				40.70				21-30	
															31-40	
Sub-basin6	0.03	Non-veg (%)	66.70	279.08	441.38	808.29	100.00	238.93	432.37	795.73	0.00	347.67	418.36	783.30	0-10	33.3
		Open-veg (%)	33.30				0.00				100.00				11-20	66.7
		T/F (%)	0.00				0.00				0.00				21-30	
															31-40	
Sub-basin7	0.003	Non-veg (%)	0.00	314.81	932.40	313.27	66.70	253.27	809.21	426.37	0.00	315.04	934.36	314.21	0-10	
		Open-veg (%)	100.00				33.30				100.00				11-20	100
		T/F (%)	0.00								0.00				21-30	
															31-40	

Sub-basin 8	0.009	Non-veg (%)	22.20	232.35	1155.70	181.19	55.60	180.35	1121.60	207.60	0.00	215.26	1102.84	254.12	0-10	
		Open-veg (%)	66.70				22.20				77.80				11-20	44.4
		T/F (%)	11.10				22.20				22.20				21-30	33.3
															31-40	22.2

5. Njaba2

The Njaba2 catchment (figure 5.18) has an area of 1.28 km^2 (Table 5.1). Reductions in tree/fallow cover were observed from 37.7% in 2009 to 3.5% in 2018 across the entire catchment, however, there was increase in fallow-cover in sub-basin 20 (sub-basin 20 covers most parts of the gully). Non-vegetated surfaces increased from 15.5% to 24.7% between 2009 and 2018, also, open vegetated areas increased from 46.8% to 71.8% within same period (figure 5.18).

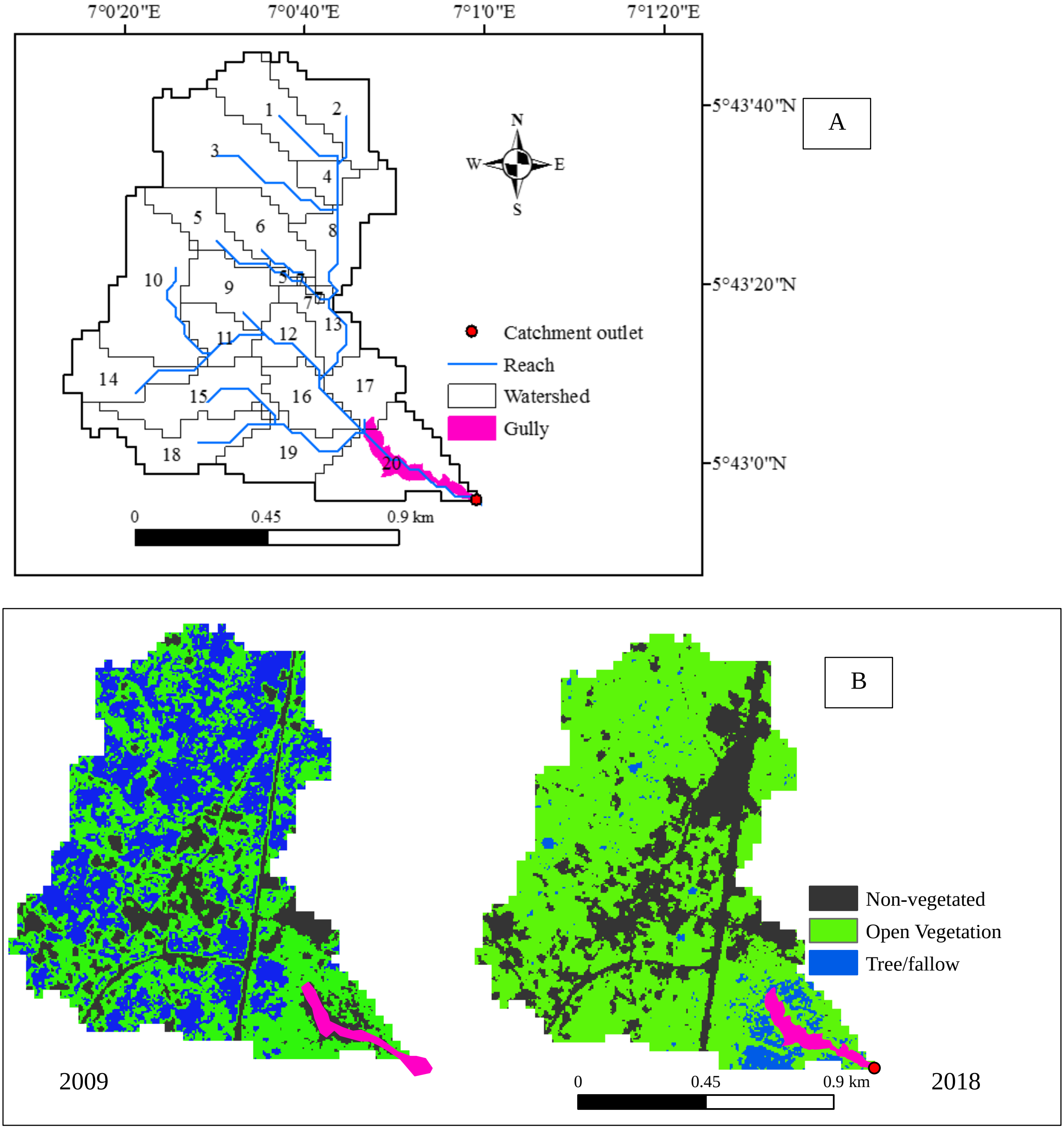

Figure 5.18: A, Njaba2 gully watershed. Gully ID, 3. Sub-basins are labelled. B, Land-use changes. There is sustained reduction in tree/fallow from 2009 to 2018 across the entire catchment, although in sub-basin 20, increase in fallow is observed. Non-vegetated surfaces remained at low-density between 2009 and 2018.

Total estimated streamflow was the same for 2009 and 2018 (21 m^3/s). Total surface runoff contribution to streamflow increased in all but three sub-basins (11, 17, 20) between 2009 and 2018 (figure 5.19). Maximum lateral flow increased in four sub-basins (10, 11, 13, 20) and reduced in the other 16. Three sub-basins (9, 17, 20) had higher percolation estimates in 2018 than in 2009 while three sub-basins (4, 7, 11) had higher maximum evapotranspiration values was in 2018 than 2009. These changes in hydrological processes are related to changes in land use within the sub-basins, e.g. increased fallow-cover in 2018 led to reductions in modelled surface runoff and increase in estimated lateral flow and percolation totals in sub-basin 20. Total rainfall was 2362 mm and 2351 mm for 2009 and 2018 respectively.

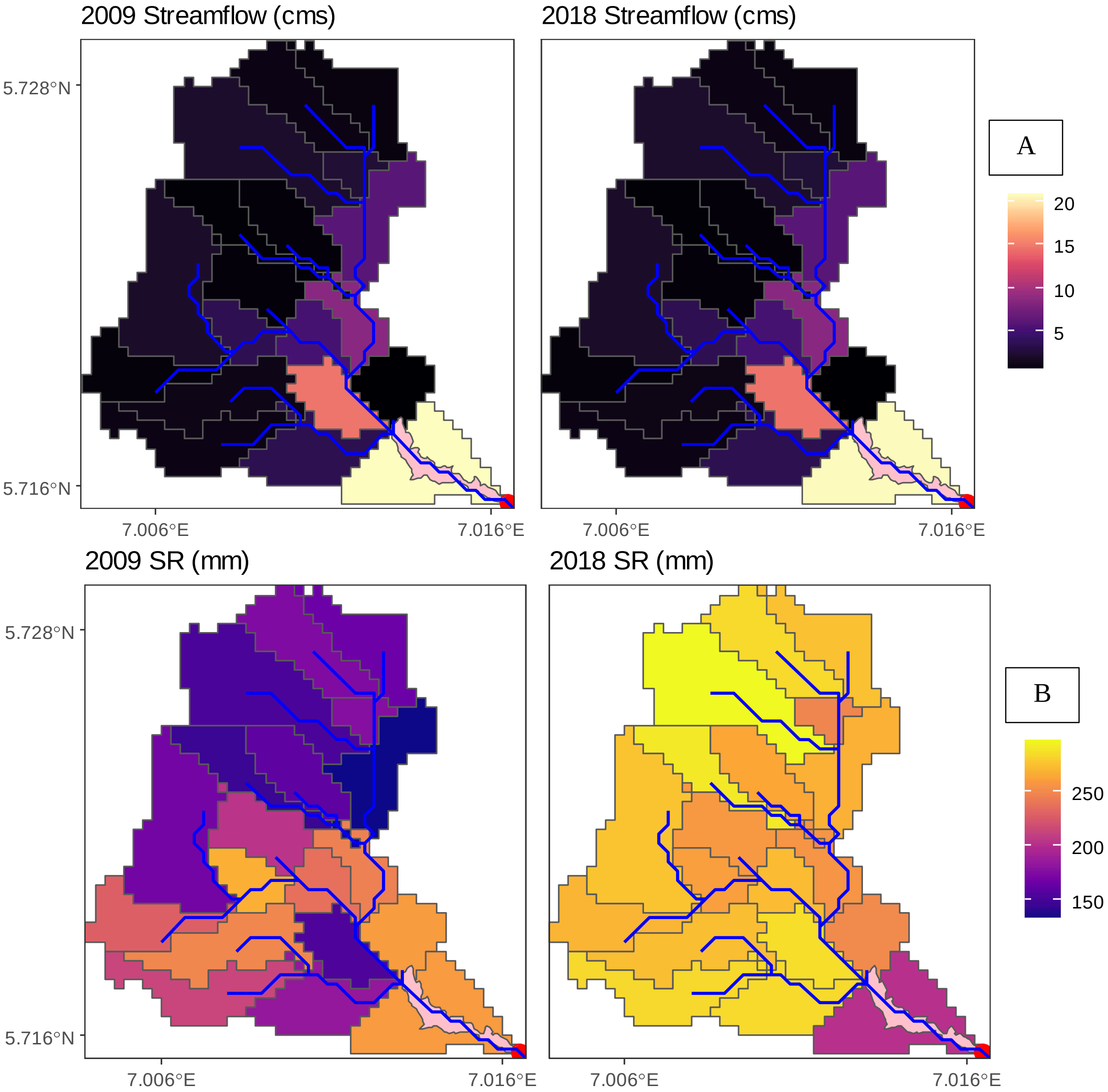

Figure 5.19: Njaba2 hydrology, A, Streamflow, B, surface runoff.

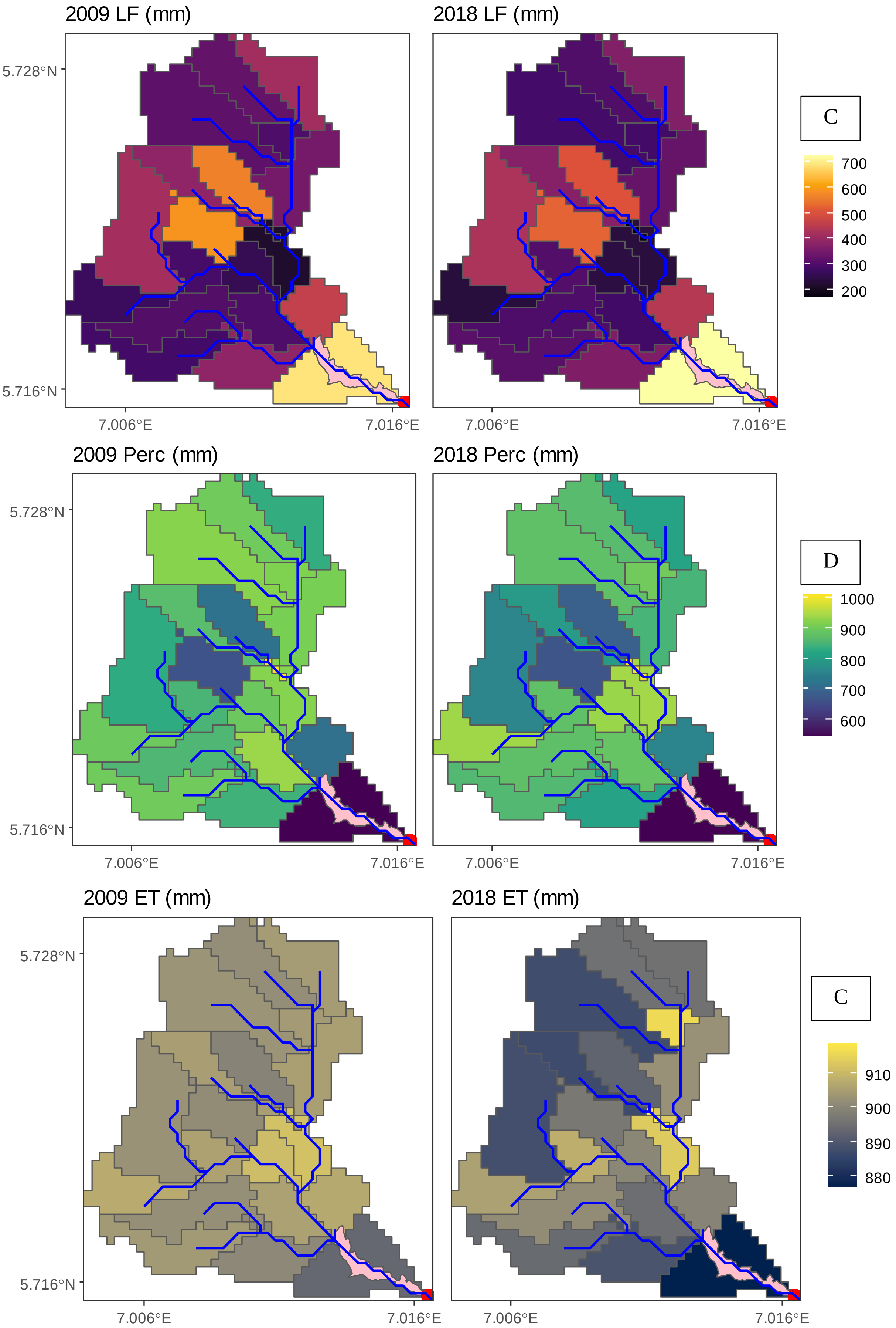

Figure 5.19 cntd: Njaba2 hydrology.

Figure 5.19 cntd: Njaba2 hydrology, A, estimated streamflow. Total flow out of the catchment remained at 21 m^3/s in 2009 and 2018. B, surface runoff contribution to streamflow. Surface runoff increased in all but three sub-basins (11, 17, 20) between 2009 and 2018 in response to land-use changes. C, lateral flow contribution to streamflow. Maximum lateral flow increased in four sub-basins (10, 11, 13, 20) and reduced in the other 16. D, percolation estimates. Three sub-basins (9, 17, 20) had higher percolation estimates in 2018 than in 2009 while reductions were observed in the remaining 17. E, evapotranspiration. 2018 has the highest evapotranspiration. Total annual rainfall was 2362 mm and 2351 mm for 2009 and 2018 respectively.

In all the five sample catchments, spatial connectivity of land use influenced streamflow into and out of individual sub-basin reaches. For example, in Njaba 2, upstream sub-basins had higher surface runoff contributions to streamflow due to reductions in fallow cover in 2018 (figure 5.19B), however, due to the higher vegetated nature of sub-basin 20, lesser runoff flow was modelled in sub-basin 20. It is also likely that surface flow from upstream sub-basins would infiltrate in sub-basin 20 thereby reducing total streamflow out of catchment, vegetated channels reduce peak flow (Frankl et al 2019) by increasing friction, reducing velocity and increasing transmission losses. With regards to gully management, proper management of upper catchments reduces runoff response (Nyssen et al. 2010), and while higher non-vegetated areas in upper catchment area may not affect the general streamflow out of a catchment (as observed in Njaba5), higher surface runoff volumes from upstream sub-basins will likely get to the gully head. This higher runoff volume may enhance gully head migration, especially, if there is scanty vegetal cover at the gully head. Higher vegetal cover at the gully head will possibly enhance infiltration of surface runoff. Infiltrated water either flows laterally, or joins groundwater flow. Both types of sub-surface flow facilitate gully evolution (Okagbue & Uma, 1987; Dunne, 1990).

5.2 Result validation

It is standard procedure to undertake validation of modelled results to ensure they reflect what is observed in the field. In the absence of observed streamflow data, results available from literature review, focus group meeting and fieldwork (section 3.2.2.1.11) were used to improve confidence in the modelled result.

Surface runoff: changes in land use, especially, increased paved surfaces, leads to increased surface runoff (section 5.1). Studies by Njoku et al. (2010), Efiong, (2011), Enaruvbe & Ige-Olumide, (2015), AC-Chukwuocha, (2015), Enaruvbe & Atedhor, (2015) and Njoku et al. (2017) from different parts of southeast Nigeria observed there have been changes in land use from vegetated surfaces to paved surfaces over the years. These authors suggested these increased paved surfaces have led to higher incidences of surface runoff. Results from the two focus group meetings (section 4.4.2) held in Amucha and Obibi-Ochasi confirmed increase in paved surfaces in both communities in the last 10 years. The respondents suggested there have been higher surface runoff volumes in their communities following increase in paved surfaces in the last 10 years (2009 – 2018), "more houses have been built while the grasses and forests have been cleared, these changes have increased surface runoff". They also blamed higher volume of surface runoff on the type of roofing sheet employed in recent times, "the use of aluminium/iron roofing sheets in building construction has increased surface runoff because many years ago, thatch roofs were used, and they produced lesser runoff". Modelled surface runoff estimates were greater in 2018 than 2009 for both watersheds (Amucha and Obibi-Ochasi).

During fieldwork, one gully under active management (Urualla_gully1 catchment) and one where gully rehabilitation works were abandoned (Umueshi catchment) were visited. At both sites, vegetation cover had been cleared while earth-moving equipment were used to work surrounding areas of the gully and thereby likely increasing compaction which may possibly reduce infiltration. At both sites, rills of different sizes were observed which indicate signs of surface flow (figures 4.10A and 5.20). Surface runoff estimates were higher in 2018 than 2009 for both catchments, and thus reflecting observations made in the field. Observed results from two visited watersheds (Urualla_gully1 and Umueshi) and focus group discussions from two catchments (Amucha and Obibi-Ochasi) support the higher estimates of 2018 surface runoff.

Sub-surface flow: during fieldwork, presence of springs and return flow were observed at two visited gully sites; Amucha and Obibi-Ochasi gully sites. Although modelled results indicate reductions in lateral flow and percolation at these catchments (Appendices 5.2 and 5.16), generous amounts of both hydrological parameters were estimated at both catchments. A video (attached as a separate document, screenshots shown in figure 5.21) of sub-surface return flow at Obibi-Ochasi catchment is evidence of high sub-surface flow in the study area as indicated in Appendices 5.2 and 5.16. Although there are no measured daily values for surface runoff or baseflow in the study area, literature review, responses from focus group meetings and field observations confirm that estimated results presented in this study are reasonable.

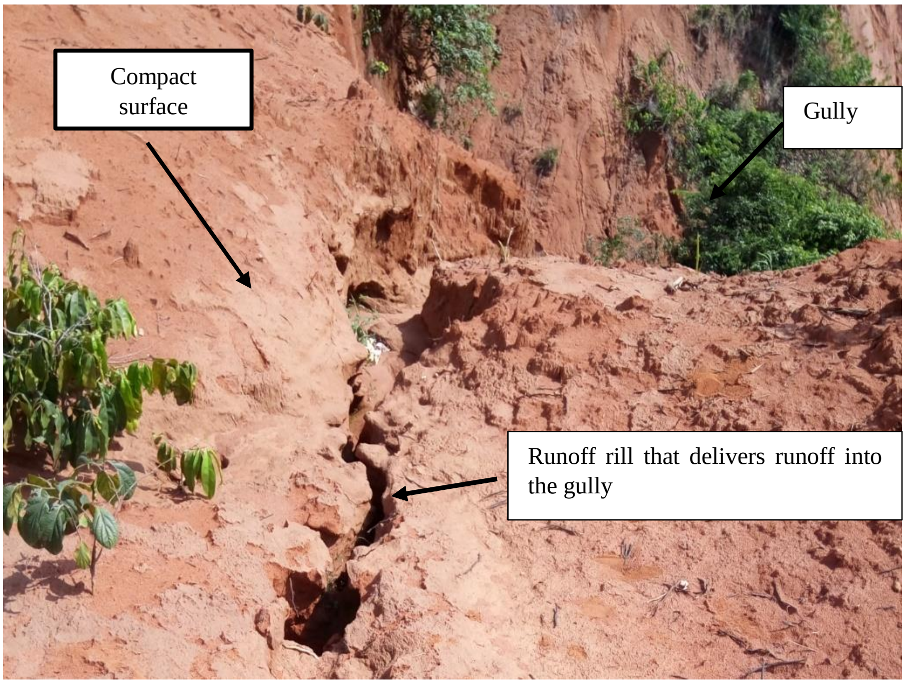

Figure 5.20: Runoff rill formed on compacted surface at the Umueshi abandoned gully rehabilitation site. Rills found close to gullies had depth ranges between 0.4 – 0.7 m, widths varied between 0.25 & 2.2 m while lengths ranged from 10 – 60 m.

Figure 5.21: Screenshots of sub-surface return flow at the older gully in Obibi-Ochasi. Video attached as a separate document.

5.3 Changes in gully sizes in response to changes in the hydrology of gully catchments

Modelled results of changes in catchment hydrology presented so far have been used to illustrate influence of changes in land use on the hydrology of catchments. It has been shown in section 5.1.2 that while there could be general change in land use in a catchment in one direction (e.g. reduction in fallow), one or two sub-basins within such catchments could experience land-use changes in the opposite direction (e.g. increase in fallow). Also, it has been noted in section 5.1.2 that spatial configuration of land use within a sub-basin influences volume of streamflow into and out of sub-basins. These variations in land-use changes within sub-basins affect hydrological processes and potentially, gully expansion. In this section, investigations to the extent to which changes in gully dimensions have been driven by changes in hydrology between 2009 and 2018 are presented. First, detailed assessments of changes in the five ‘sample catchments’ are given while summary changes are provided for the remaining gully catchments. Tables 5.5, 5.6 and 5.7 illustrate changes in gully characteristics from 2009 to 2018 across the 22 gully catchments.

In IdNorthWS (figure 5.9), gully lengths were 0.1, 0.1 and 0.11 km, the average widths were 34.09, 38.07 and 44.17 m while gullied areas were 3557, 3954 and 4902 m^2 for 2009, 2014 and 2018 respectively (Table 5.5). Figure 5.17 shows that during intervening years, variations in rainfall leads to variations in both surface runoff and general streamflow. In the IdNorthWS catchment for example, maximum surface runoff values were 261 and 224 mm while total streamflow volumes were 9.1 and 8.9 ms^{-3} and rainfall totalled 2489 and 2403 in 2011 and 2012 respectively (Table 5.8). 2010 and 2013 were drier than 2014 (figure 5.17). Despite the increase in runoff contribution to streamflow between 2009 and 2014 and reduction in lateral flow across the IdNorthWS catchment, but especially, in sub-basins adjacent to the gully (figure 5.10, Table 5.8), no change was recognised in gully length for this period (Table 5.6). However, a 10 m growth of gully length was observed between 2014 and 2018 (Table 5.6) corresponding to increase in lateral flows (Table 5.8) and percolation particularly in the sub-basins bordering the gully and higher estimates of surface runoff from upstream sub-basins (figure 5.10). Gully width widening occurred during both time periods. Thus, it is possible that surface runoff facilitated the lateral growth of the gully between 2009 and 2014, while surface and sub-surface flows influenced longitudinal and lateral gully expansions between 2014 and 2018.

Table 5.5: Changes in gully characteristics between 2019 and 2018. Gullies not covered by the 2014 satellite imagery have no cell-values.

number	Catchment id	Gully length 2009 (km)	Average width 2009 (m)	Area 2009 (m^2)	Gully length 2014 (km)	Average width 2014 (m)	Area 2014 (m^2)	Gully length 2018 (km)	Average width 2018 (m)	Area 2018 (m^2)
1	IdNorthWS	0.1	34.09	3557	0.1	38.07	3954	0.11	44.17	4902
2	IdSouthWS1	0.16	35.67	5879	0.2	32.14	6935	0.2	30.53	6589
3	NjabaWS1	0.5	30.31	15166	-	-	-	0.5	36.42	19371
4	Amucha	0.7	43.63	32508	-	-	-	0.9	56.68	52462
5	IdeatoNorth	1.2	31	39183	-	-	-	1.2	44.84	53182
6	IdeatoNorth1	0.46	30.85	11270	-	-	-	0.5	29.11	16929
7	IdeatoSouth_gully1	0.3	27.81	8125	0	0	0	0.6	31.07	19892
8	IdeatoSouth_gully2	0	0	0	0.36	12.3	5060	0.56	23.4	13533
9	IdeatoSouth3	0	0	0	0.1	10.9	1102	0.19	14.51	2850
10	Isu_gully1	0.22	49	10622	0.32	45	14835	0.33	57.3	21497
11	Isu_gully2	0.19	42.3	8203	0.2	50.14	10402	0.22	55	14170
12	Isu_gully3	0.06	31.4	1723	0.06	31.4	1723	0.23	50	11661
13	Njaba2	0.5	31.8	18027	-	-	-	0.4	44.89	18804
14	Njaba4	0.3	15.23	4865	-	-	-	0.5	23.29	11287
15	Njaba5	0	0	0	-	-	-	0.5	18.37	10008
16	Orlu1	1.4	19.76	29442	-	-	-	2	31.46	57679
17	Orlu2	0.45	39.22	22489	-	-	-	0.53	38.25	24480
17	Orlu2	0.29	40	9557	-	-	-	0.65	60	34105
18	Urualla_gully1	0.8	38.66	38164	-	-	-	0.9	38.86	52081
19	Urualla_gully2	0.36	25.37	9235	-	-	-	0.7	27.87	16236

20	Urualla_gully3	0.93	59.24	47530	-	-	-	0.98	72.23	52235
21	Orlu3	0	0	0	-	-	-	0.5	50.69	23192
22	Umueshi	0.33	51.1	17031	-	-	-	0.37	57.6	20060

Table 5.6: Summary changes in gully sizes for catchments captured in the 2009, 2014 and 2018 satellite data.

Catchment	Change in length 2009 – 2014 (m)	Change in width 2009 – 2014 (m)	Change in area 2009 – 2014 (m^2)	Change in gully length 2014 – 2018 (m)	Change in gully width 2014 – 2018 (m)	Change in gullied area 2014 – 2018 (m^2)
IdNorthWS	0	3.98	398	10	6.1	948
IdSouthWS1	40	-3.53	1056	0	-1.61	-347
Ideatosouth_gully1	-	-	-	600	31.07	19892
Ideatosouth_gully2	360	12.3	5060	200	11.1	8472
Ideatosouth3	100	10.9	1102	90	3.61	1748
Isu_gully1	104	-4	4213	12	12.3	4213
Isu_gully2	6	7.84	2199	20	4.86	3768
Isu_gully3	0	0	0	170	18.6	9938

Table 5.7: Summary changes in gully sizes for catchments captured in the 2009 and 2018 satellite data.

Catchment	Change in gully length 2009 – 2018 (m)	Change in gully width 2009 – 2018 (m)	Change in gullied area 2009 – 2018 (m^2)
NjabaWS1	0	6.11	4205
Amucha	200	13.05	19955
IdeatoNorth	0	13.84	14000

IdeatoNorth1	40	-1.73	5659
Njaba2	-100	13.09	777
Njaba4	200	8.06	6422
Njaba5	500	18.37	10008
Orlu1	600	11.7	28237
Orlu2	80	-0.97	1992
Orlu2	360	20	24548
Urualla_gully1	100	0.2	13918
Urualla_gully2	340	2.5	7001
Urualla_gully3	50	13	14000
Orlu3	500	50.69	23192
Umueshi	40	6.5	3029

Table 5.8: IdNorthWS variation in modelled hydrological processes for intermediate years.

	Year	Maximum runoff (mm)	Lateral flow (mm)			Streamflow (m^3/s)	Rainfall (mm)
Gully adjacent sub-basins			8	9	10		
	2009	226	369.12	535.54	752.75	9.1	2447
	2011	261	360.88	525.58	739.58	9.1	2489
	2012	225	350.98	508.94	713.14	8.9	2403
	2014	262	342.93	493.06	698.82	8.9	2411
	2017	308	356.24	475.25	730.88	8.9	2411
	2018	334	368.84	493.05	762.88	18	2443

In the IdSouthWS1 gully catchment, there was an increase in gully length by 40 m between 2009 and 2014 (Table 5.6). No further increase was observed in the headward extension for the years 2014 and 2018 and there was continuous reduction in gully width from 2009 to 2018. Increase in gully length/headward extension corresponded to higher surface runoff contribution to streamflow in 2011 and 2012 (figure 5.17B) and higher lateral flow and percolation in sub-basins 3 and 4 in 2014 compared to 2009 (figure 5.17). Sub-basins 3 and 4 are adjacent to the gully. Sustained reduction in gully width is likely due to vegetal colonisation evidenced in the increase in tree/fallow-cover in the IdSouthWS1 catchment (figure 5.16) which is capable of concealing the actual width of the gully.

In Njaba2 catchment (figure 5.18), gully lengths were 0.5 and 0.4 km, widths measured 31.80 and 44.89 m while gullied areas were 18027 and 18804 m^2 for 2009 and 2018 accordingly (Table 5.5). Thus, while gully length apparently reduced by 100 m, there were lateral and areal expansions of 13.09 m and 777 m^2 between 2009 and 2018 (Table 5.7). Higher width and area values corresponded to higher surface runoff in all but three sub-basins that witnessed reduced estimates of surface runoff (11, 17, 20), increased lateral flows and percolation especially in sub-basins 17 and 20 which cover the gully (figure 5.19). Apparent reductions in gully dimensions between 2009 and 2018 possibly resulted from increased vegetal cover (there was increase in fallow-cover in sub-basin 20, figure 5.18) which may have covered the real dimensions of the gully length. In these three gully catchments, IdNorthWS, IdSouthWS1 and Njaba2, growth of gully sizes (length, width or area) corresponded with higher volumes of sub-surface flows (lateral flow and percolation estimates) especially in gully-adjacent sub-basins.

The gully in IdeatoSouth_gully1 catchment, is thought to have been managed/sand-filled sometime between 2009 and 2014 as the gully was not visible in the 2014 satellite data. This gully reappeared in the 2018 satellite data, and modelled surface runoff increased between 2014 and 2018 in all but two sub-basins (7 and 9). These two sub-basins deliver water into the gully from the sides as the gully head is located in sub-basin 5 (figure 5.11). Reductions in lateral flow was simulated in sub-basins 1 and 2 while the other sub-basins had higher estimates of lateral flow. Therefore, it is likely that gully expansion post-2014 was driven by increase in both surface and lateral flows at this catchment. With regards to IdeatoSouth_gully2 catchment, no gully was identified in the 2009 imagery and increase in gully dimensions post the 2014 satellite data corresponded with higher surface flow and reduced lateral flow estimates between 2014 and 2018 across all sub-basins. In NjabaWS1 (Appendix 5.1), longitudinal extension of the gully was not observed between 2009 and 2018 (Table 5.7) despite a higher surface runoff estimate across all sub-basins in 2018 compared to 2009. Lateral and areal gully expansions were observed which corresponded to an increase in lateral flow in sub-basin 2 and higher percolation in sub-basin 5. Both sub-basins deliver flow directly into the gully.

Higher surface runoff, lower lateral flow and percolation values were modelled for the Amucha catchment (Appendix 5.2) between 2009 and 2018 and these modelled results corresponded to 200 m, 13.1 m and 19955 m^2 increase in gully length, width and area, accordingly (Table 5.7). The IdeatoNorth gully catchment experienced increase in estimated surface runoff and reductions in lateral flow and percolation between 2009 and 2018 (Appendix 5.3), and in the same period, no headward retreat was observed while lateral and areal retreats of 13.8 m and 14000 m^2 were recorded (Table 5.7). In the IdeatoNorth1 watershed (Appendix 5.4), higher estimates of surface runoff, lower lateral flow and percolation corresponded with a 40 m headward extension of the gully between 2009 and 2018. Although, there was reduction in gully width within same period, areal expansion of 5659 m^2 was recorded (Table 5.7). No gully was found in the 2009 satellite data of the IdeatoSouth3 catchment however, a gully was identified in the 2014 imagery. There was increase in estimated surface runoff in all the sub-basins in the Ideatosouth3 catchment (Appendix 5.5), between 2014 and 2018. 10 sub-basins, including sub-basin 12 (the gully in this catchment is found in sub-basin 12) experienced increase in lateral flow. There was increased estimate of percolation in sub-basin 12 as well. These estimated changes in modelled hydrological processes related to gully head retreat of 90 m, lateral and areal expansions of 3.61 m and 1748 m^2 between 2014 and 2018 (Table 5.6).

There was increase in surface runoff in all but two sub-basins (2 and 4) in the Isu_gully1 catchment. Equally, there were increases in modelled lateral flow and percolation in sub-basins 2, 5 and 6 between 2009 and 2014 (Appendix 5.6). During the same period, gully length increased by 100 m. Reductions in surface runoff estimate were recognised in sub-basins 2 and 5 while higher lateral flow was identified across the sub-basins (except sub-basin 7) between 2014 and 2018. Gully length, width and area increased by 12 and 12.30 m and 4213 m^2 respectively between 2014 and 2018 (Table 5.6). In Isu_gully2 catchment (Appendix 5.7), increase in surface runoff was estimated in all but three sub-basins (2, 7, 8) between 2009 and 2014. During same period, there were reductions in lateral flow across all sub-basins and these changes in modelled estimates corresponded with gully areal retreat of 2199 m^2. Between 2014 and 2018, increase in lateral flow across all sub-basins was estimated, and these higher lateral flow values related to 20 and 4.9 m headward and lateral expansions of the gully respectively (Table 5.6). The Isu_gully3 catchment (Appendix 5.8) experienced increase in estimated surface runoff in all but two sub-basins (1 and 6) while lateral flow and percolation estimates reduced between 2009 and 2014. No change was identified in the gully sizes during this period (Table 5.6). There was increased surface runoff between 2014 and 2018 in all sub-basins except 2,5,7, also, higher percolation was modelled for sub-basin 2 and 7. During the same period (2014 – 2018), gully length and width retreats of 170 m and 18.6 m were recorded (Table 5.6).

In the Njaba4 catchment (Appendix 5.9), increased estimates of surface runoff and subsequent reductions in lateral flow and percolation corresponded with 200 m increase in gully length and 6422 m^2 areal expansion between 2009 and 2018 (Table 5.7). Modelled surface runoff estimates in the Njaba5 catchment (Appendix 5.10) were higher in 2018 than 2009 across all sub-basins. Also, both lateral flow and percolation values of 2009 were greater than those of 2018 and a gully headward extension of 500 m was recognised during same period (Table 5.7). The Orlu1 and Orlu2 watersheds are urbanised watersheds in the study area (Appendices 5.11 and 5.12). There were increased estimates of surface runoff, reduced lateral flow and percolation volumes between 2009 and 2018. Gully sizes increased with an increase in surface runoff (Table 5.7).

Estimated surface runoff was higher in all but four sub-basins (3, 8, 9, 12) in the Urualla_gully1 catchment (Appendix 5.13). The gully in this catchment was under management as at the time of field visit. Gully length increase (100 m between 2009 and 2018) was recorded in this catchment as well (Table 5.7). The Urualla_gully2 catchment (Appendix 5.14) experienced increased estimates of surface runoff, reduced percolation and lateral flow volume between 2009 and 2018. During the same period, gully areal expansion of 7001 m^2 was recorded (Table 5.7). There was increase in estimated surface runoff in all sub-basins of the Urualla_gully3 catchment (Appendix 5.15). Lateral flow estimates of 2009 were higher than those of 2018 in all but one sub-basin (sub-basin 2), equally, there was reduction in modelled percolation in all sub-basins between 2009 and 2018. Gully length and width increased by 50 and 13 m between 2009 and 2018 (Table 5.7).

Results from focus group meetings suggest that the gully in the Obibi-Ochasi catchment (Appendix 5.16) is one of the oldest gullies in the state (formed in 1968). However, due to thick vegetal cover (figure 5.22), the gully was not visible in the 2009 satellite imagery. The gully was mapped using the 2018 imagery at a length of 500 m. There was increase in estimated surface runoff across all sub-basins. Also, estimated lateral flow in 2009 was higher for all sub-basins than in 2018 except in sub-basin 3 which is at the head of the gully. In the Umueshi catchment (Appendix 5.17), increased surface runoff and reductions in lateral flow and percolation volumes were estimated between 2009 and 2018. During the same period, gully length increase of 40 m and areal expansion of 3029 m^2 were recorded (Table 5.7).

Despite similarities in soil type and climate, modelled results varied from catchment to catchment based on variations in land use and other local factors such as slope angles of sub-basins. Gully changes also varied from one catchment to another. While gully length, width and areal expansions related to increases in surface flow in some catchments, gully growth corresponded to sub-surface flow changes in others (Table 5.9). Yet in some watersheds, as increased surface and sub-surface flows were modelled across different sub-basins, changes in gully dimensions occurred. In summary, modelled results point to the uniqueness of individual gully catchments and gully responses to this uniqueness is important for gully management. These results also suggest there is a continuum in the actions of both sub-surface and surface flows as gully drivers in the study area. Finally, results presented in this section have shown that gullies in the study area responded to changes in catchment hydrology (reduction or increase in surface and sub-surface flows) and thereby providing answers to the second research question.

Table 5.9: Summary changes in gully dimensions in response to changes in catchment hydrology. N = no, Y = yes, SR = surface runoff.

Increase in length alongside increase in SR	Increase in width alongside increase in SR	Increase in area alongside increase in SR	Increase in length alongside increase in sub-surface flow	Increase in width alongside increase in sub-surface flow	Increase in area alongside increase in sub-surface flow	Catchment
N	Y	Y	N	Y	Y	NjabaWS1
Y	Y	Y	N	N	N	Amucha
N	Y	Y	N	N	N	IdeatoNorth
Y	N	Y	N	N	N	IdeatoNorth1
Y	Y	Y	Y	Y	Y	IdeatoSouth3
Y	Y	Y	Y	Y	Y	Isu_gully1
Y	Y	Y	Y	Y	Y	Isu_gully2
Y	Y	Y	Y	Y	Y	Isu_gully3
Y	Y	Y	N	N	N	Njaba4
Y	Y	Y	N	N	N	Orlu1 and Orlu2
Y	Y	Y	Y	Y	Y	Urualla_1
Y	Y	Y	N	N	N	Urualla_gully2
Y	Y	Y	N	N	N	Urualla_gully3
Y	Y	Y	Y	N	N	Obibi-Ochasi
Y	Y	Y	N	N	N	Umueshi

Figure 5.22: Vegetal cover growing inside and around gully edges at the older Obibi-Ochasi gully. This gully started in 1968 but was not captured in the 2009 satellite data due to vegetal cover.

5.4 Discussion

5.4.1 Changes in catchment hydrology in response to land-use changes: implications for surface runoff-driven erosion

Conversion of land from vegetated to paved surfaces increases surface runoff contribution to streamflow (figures 5.3. and 5.5). Conversely, higher vegetal cover reduces surface runoff contribution to streamflow while enhancing infiltration to deep aquifer-recharge. Water is lost through a catchment by deep aquifer recharge, thus, reducing volume of streamflow (figure 5.17C). Despite having a uniform amount of rainfall (2362 mm) for both 2009 and 2018, there was an increase in surface runoff contribution to streamflow in the Orlu1 catchment from a minimum estimated value of 166 mm in 2009 to 390 mm in 2018, and a similar increase in maximum runoff estimate from 533 mm in 2009 to 797 mm in 2018 (figure 5.5B). During the same period, non-vegetated surfaces increased from 26.2% to 63.7%. Streamflow estimates were either the same in 2009 and 2018 or greater in 2018 across the five catchments whose results were presented, yet 2009 was the wettest year. These increased streamflow estimates are due to higher volumes of surface runoff and lesser deep aquifer recharge. Njoku et al. (2017) made a similar observation in Owerri the Imo State capital. They concluded that increased paved surfaces caused by higher urbanisation of the state capital from 1986 to 2016 had increased incidences of surface runoff and flooding in the city. Significant increase in discharge was observed in the Gumara catchment, Ethiopia between 1986 and 2015, yet no significant change was identified in rainfall regime during same period (Birhanu et al. 2019). Higher streamflow discharge was attributed to increase in: urban and bare surfaces, cultivated lands and reductions in grazing and forested lands (Birhanu et al. 2019). Higher surface runoff increases incidence of gully erosion through surficial removal of soil particles along rills and gullies (Attah et al. 2013; Okagbue & Uma, 1987).

Two types of changes were observed in the non-vegetated class in some of the modelled catchments (e.g. IdeatoSouth_gully2), one was increase in land area under non-vegetated class and the other was increase in connectivity of non-vegetated surfaces. Thus, in some catchments, non-vegetated class changed from low-density to medium (IdeatoSouth_gully1, IdeatoSouth_gully2) and in others, they remained at low-density (IdNorthWS1, IdSouthWS1 and Njaba2). Curve Numbers for these land-cover classes are different (Table 3.6) and have implications on modelled runoff and streamflow. For example, change from low to medium density means higher estimates of surface runoff and increased runoff contribution to streamflow into and out of a channel reach. Based on the configuration of land use in a catchment, there could be higher surface runoff contribution to flow in the upper section of a catchment, but reduced streamflow out of the downstream reaches. This variation potentially affects gully-driving processes. For example, higher surface runoff flowing into the gully head will likely increase headcut retreat rates especially, when the gully head is sparsely vegetated. However, higher vegetal cover in the lower section of same gully will potentially increase infiltration and reduce the process of surface runoff erosion. If the gully head is vegetated, higher surface runoff flowing from upstream areas may infiltrate and enhance sub-surface erosion at the gully head. Therefore, it is possible that different hydrological processes will be at work in different sections of a gully based on land use configuration of not just the entire catchment, but also of the sub-basin where the gully is found.

While human-induced land-use changes are recognised in this work, natural occurrences (such as prolonged period of dry season) that enhance reduction in vegetal cover will also increase surface runoff and likely facilitate surficial erosion of gully walls. With regard to seasonal variation in vegetal cover, at the beginning of rainy season (March – April) when vegetation cover is at its minimum, the role of surface runoff as an agent of gully expansion is likely to be more pronounced (figure 5.23). This condition is enhanced by the reduced vegetal cover of the land and likely compaction of bare soils by both human and animals, both activities encourage surface runoff flow (Yibeltal et al. 2019). The dry season is not the only reason for reduction in vegetal cover at the outset of the rainy season. Bush burning (figure 5.24), an agricultural practise which is observed at the beginning of farming season (March/April) also plays a role in the removal of vegetal cover.

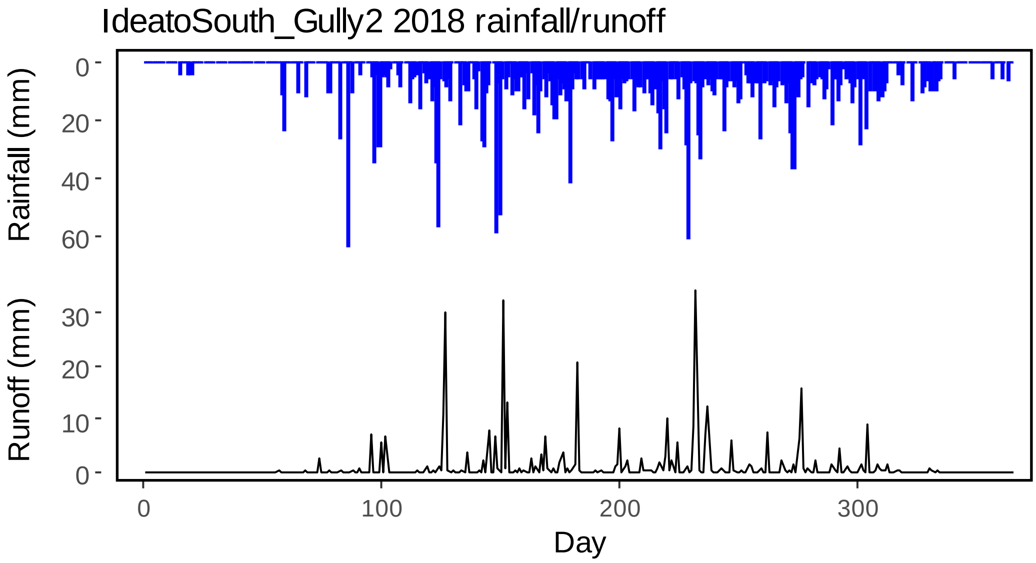

Figure 5.23: IdeatoSouth_Gully2 daily rainfall/runoff. Influence of runoff as a gully-driver will likely be dominant in the beginning of rainy season March/April (90th – 120th day of the year).

Bush burning leaves the soils without vegetation cover as the rains start in earnest and thereby increasing susceptibility to erosion (Igwe et al. 2014). Thus, combinations of 4/5 months of dry season (November – March) and bush burning an agricultural activity ensure soils are bare before the outset of rainy season. The work of surface runoff as a gully driver which manifests in gradual removal of soil particles (Okagbue & Uma, 1987) is likely to be more evident as long as favourable conditions exist (e.g. sparse vegetal cover) until a time when vegetation growth increases in response to availability of moisture. At this stage there is increased infiltration due to higher green-cover, and subsequent increase in sub-surface flow. Also, runoff may occur from saturation overland flow when there is higher vegetal cover and while saturation overland flow may not cause as much surface erosion because of the protection from vegetation cover, it might lead to gully expansion from subsurface erosion.

Figure 5.24: Bush burning so as to prepare the land for cultivation, this farming technique which happens just before the outset of rainy season leaves the soils bare and without vegetal cover.

5.4.2 Sub-surface driven erosion

During fieldwork, soil pipes were not observed but considering the non-cohesive nature of soils under investigation in this study (section 4.4.1), Coloumb failure (section 2.1) as a process of seepage erosion is likely dominant in the study area. Poesen, (2018) remarked that significant feedback mechanisms between erosion and hydrological processes are not yet fully understood. In this study, modelling results suggest that slope gradient strongly influences the volume of lateral flow. Sub-basins with steep slopes produced higher volumes of estimated lateral flow (e.g. sub-basins 9 and 10 of Table 5.3 and figure 5.10) perhaps capable of eroding gully walls, conversely, higher percolation values were estimated in sub-basins with gentler slopes (e.g. sub-basin 5 of Table 5.3 and figure 5.10). This observation helps improve our knowledge on hillslope hydrology and erosional processes, thus, broadening our view from the correlation of higher slope angles with increased surface runoff (Gómez-Gutiérrez et al. 2015), to a new idea where we appreciate the relationship between higher slope gradients and lateral flow as a potential gully erosion driver. In relation to changes in gully dimensions, it is likely both surface and sub-surface processes influence gully evolution such that higher surface runoff flowing into the gully head from upstream sub-basins could be driving headward extension, while sub-surface flow, especially from gully-surrounding sub-basins, is responsible for lateral widening or vice versa. An example where gully expansion responded to increases in both surface and sub-surface flows is found in the IdNorthWS catchment (figure 5.10).

Groundwater flow-driven gullying involves different processes of landsliding thus while surface runoff gradually removes soil particles, groundwater actions involve removal of earth materials in larger volumes (Okagbue & Uma, 1987). Considering the depths of visited gullies (> 15 m, figure 5.25), presence of springs (figure 5.21) and landslide scars, it is possible gullies under investigation in this study are at the fourth stage of evolution proposed by Okagbue and Uma (1987) (section 2.1). Published studies have indicated that active gullies are located mostly at the discharge areas of groundwater systems as well as in areas where the water tables are above the gully bottom (Egboka & Okpoko, 1984; Egboka & Nwankwor, 1985; Tebebu et al 2010). Elevated groundwater appears to enhance gully destabilization by facilitating slumping which results in gully widening and expansion. Slumping occurs because the pore water pressure above the gully bottom pushes the soil out when soils are saturated, and the pore water pressure is greater than the soil strength (Tebebu et al 2010). Thus, the elevated water table causes the rapid upslope migration of the gully head. When the water table is below the gully bottom, the soil is unsaturated and maintains some degree of cohesive strength. Therefore, gully widening in unsaturated soils is caused by surface runoff entering the gully, but this gully expansion occurs at much lower rates than when the soil is saturated (Tebebu et al 2010). This explanation could be the mechanism driving gully expansion in the IdNorthWS gully catchment where despite increase in estimated surface runoff, no changes were observed in gully length, yet width-widening was recorded between 2009 and 2014 in response to higher surface runoff (Table 5.6).

Groundwater discharge at the surface as well as slumping were observed at visited gullies thus suggesting groundwater control on gully evolution in the study area. It is important to note as well that groundwater could return to the surface as return flow thereby contributing to general surface runoff discharge (figure 5.21) and deepening existing gullies (Bernatek-Jakiel & Poesen, 2018). Return flow results from the downslope decrease in the capacity of the soil to transmit sub-surface flow (Dunne, 1990).

Piping refers to the formation of linear voids (pipes) by concentrated flowing water in soils or in unconsolidated or poorly consolidated sediments (Jones, 2004). Swanson et al (1989) remarked that dispersive soils, low in clay content are susceptible to sub-surface erosion. They recorded subsurface tunnel networks that drained into large, open gullies through tunnel outlets elevated on gully walls. According to Swanson et al (1989), this last condition suggests that the lowered base levels produced by large gullies may be a prerequisite for extensive piping upslope by providing increased hydraulic gradients to drive the subsurface erosion. Other authors have identified the occurrence of steep hydraulic gradient as a favourable condition for piping (Farifteh & Soeters, 1999; Díaz et al. 2007). Thus, in a positive feedback mechanism, sub-surface flow can increase susceptibility to gully erosion, while once gullies are formed, they can enhance vulnerability of soils to sub-surface flows by increasing hydraulic gradients (Frankl et al. 2016). Swanson et al (1989) also observed that presence of springs in a gully is evidence of sub-surface flow. Uprooted trees and bushes may increase sub-surface erosion because the holes left behind by decayed roots can cause soil cracking and accelerate downward water movement (Jones 1968).

In this study area, particle size distribution results show that the soils are low in clay content (section 4.4.1). Fieldwork revealed that animal burrows are common in the area under investigation. Even though extensive tunnel networks that drain into gullies were not observed, it is possible the sheer sizes of visited gullies (figure 5.25) could provide hydraulic gradients capable of driving sub-surface erosion on adjacent hillslopes. Springs were observed and documented at visited gullies, especially, in Obibi-Ochasi and Amucha. Finally, bush burning is a common agricultural practise in the study area as already mentioned. It is possible that the roots of shrubs and fallow left behind after bush burning can enhance transmission of surface water underground, and thus facilitate sub-surface erosion. These factors strongly suggest that sub-surface erosion occurs in the study area as supported by increase in gully sizes with higher estimates of sub-surface flows, especially, in gully-adjacent sub-basins (e.g. Njaba 2 and IdSouthWS1).

Figure 5.25: Section of the older gully in Obibi-Ochasi community showing gully depth. Pictured man is used for scale.

5.5 Chapter summary

The objectives of this chapter were to understand how variations in land use affect gully catchment hydrology and in turn, influence changes in gully characteristics and to achieve these objectives, two research questions were posed. A total of 22 gully catchments (figure 5.1) were studied in this chapter. There have been changes in gully catchment hydrology in response to land-use changes. While changes in land use in one direction across a catchment is possible (e.g. increase in non-vegetated surfaces), changes in the opposite direction in individual sub-basins (e.g. reduction in non-vegetated surfaces) were observed, and these variations had implications for modelled catchment hydrology and in turn, gully evolution.

While detailed results for 2009, 2014 and 2018 have been presented in this chapter, modelled hydrological processes for intermediate years were also presented (section 5.1.2). Inference from modelling results suggest that some catchments experienced increases in gully sizes in response to higher surface flow estimates (e.g. Amucha, Orlu1 and Orlu2), others had gully growth with higher estimates of sub-surface flow (e.g. IdNorthWS), and in some, gully expansions were observed in areas where both surface and sub-surface flows increased (e.g. IdSouthWS1, Njaba2). Modelling results suggest that in some catchments (e.g. IdNorthWS), lateral expansion in the first years of analysis (2009 – 2014) was driven by higher surface runoff, while in the later years of the analysis (2014 – 2018), both surface and sub-surface flows dominated as gully-expansion drivers. Despite the relatively small size of the study area (534 km^2), similarities in soil, topography and climate, it is difficult to say explicitly that a single process was responsible for gully evolution across the entire study site thus acknowledging uniqueness of various catchments. It is safer to say there is a continuum in both surface and sub-surface flow processes as agents of gully expansion, such that higher surface flow from sub-basins in the upstream section of the gully possibly enhance gully head retreat, while higher lateral or groundwater flow from surrounding sub-basins influences gully lateral expansion.

While it was not possible to validate the estimates of surface and sub-surface flows with observed data due to the unavailability of these data, result validation in this chapter has been conducted using three methods: literature review, observations from fieldwork and responses from focus group meetings.

5.6 Conclusions

The following conclusions are made:

1. Catchments that experienced increased non-vegetated surfaces and change in non-vegetated class (e.g. from low density to medium or high density) had higher modelled surface runoff contribution to streamflow. In these catchments, reductions in sub-surface flow were modelled.
2. In contrast to the above point (1), higher sub-surface flow volumes were modelled in areas/sub-basins that had increased tree/fallow-cover. In these areas, reductions in surface flow were estimated.
3. Inference from modelling results and analysis of gully sizes during the study period suggest that combinations of surface runoff and sub-surface flows enhance gully erosion in the study area.
4. Despite the relatively small size of the study area, it is difficult to attribute gullying to one process, thus implying that uniqueness of gully catchments is important in understanding individual gully evolutions.
5. Results from literature review, focus group meetings and field visit support the notion of increased surface runoff during the study period.
6. Observations from fieldwork support the concept of sub-surface flow control as a gully driver.

Chapter 6

Gully-landslide interactions

6.0 Introduction

Chapter 6 provides answers to questions raised by objective 3, to understand the influence of land-use changes on gully-landslide interactions. The following research question is posed: how will changes in land use and catchment hydrology affect gully-landslide interactions? Chapter 6 is presented in the following sections: results of identified landslides and a conceptual model of gully expansion by landsliding are shown in section 6.1. Section 6.2 summarises effects of land-use changes on gully landslide interactions while discussion follows in 6.3. Chapter summary and conclusions are presented in 6.4 and 6.5 accordingly.

6.1 Identified gully-induced landslides and sensitivity analysis of slope stability

Gully-induced slides were observed at all the five communities visited during field work (Amucha, Obibi-Ochasi, Isu Njaba, Umueshi and Urualla, figure 4.21). For example, the entire stretch of the Amucha gully (figure 6.1) showed old and fresh landslide scars. Table 6.1 and Figure 6.2 show multiple failures at one of the landslide sites in the Amucha gully and they range from complex failures to shallow debris slides. At slide 1 for example, four fresh scars were identified (three are pictured in figure 6.2), and their slope angles varied between 25° and 38° while runoff distances ranged between 7.7 to 15 m. These slides were also shallow with depth ranges of 1.4 – 1.5 m and widths of 2.2 – 3 m. The entire length of the gully top was vegetated; however, figure 6.2 was sparsely vegetated. Due to the active nature of the slides, establishment of vegetation colonies could prove challenging, hence, the scanty vegetal cover on landslide scars.

Soils in the Amucha gully sites are sandy and have low cohesion values (Section 4.4.1) and thus may have little resistance to erosive forces (Okagbue & Ezechi, 1988). Observation during fieldwork showed that the entire gully floor turns into a flowing stream after rains, thereby possibly removing toe support which potentially leads to further destabilisation of the gully (Igwe. et al. 2014). Both these processes occurring simultaneously can increase susceptibility of these landslide sites to further gully-induced sliding. Two gullies were visited in the Obibi-Ochasi Community; one began in 1968 and the other was said to be less than two years old as at the time of visit. Shallow debris slides were observed in the older gully while soil fall, and block failure were the dominant sliding activities in the younger gully (section 6.12). The Isu Njaba gullies exhibited signs of block failure while the Urualla gully was under management which involved reworking gully slopes (observed in the field). Although landslide measurements were not conducted in the other gullies, signs of stream flow at gully floors were observed while gully surrounding lands on gully top were vegetated except at the Urualla site which is under management. Stream flow through these gully floors will likely enhance gully wall destabilisation by removing toe support.

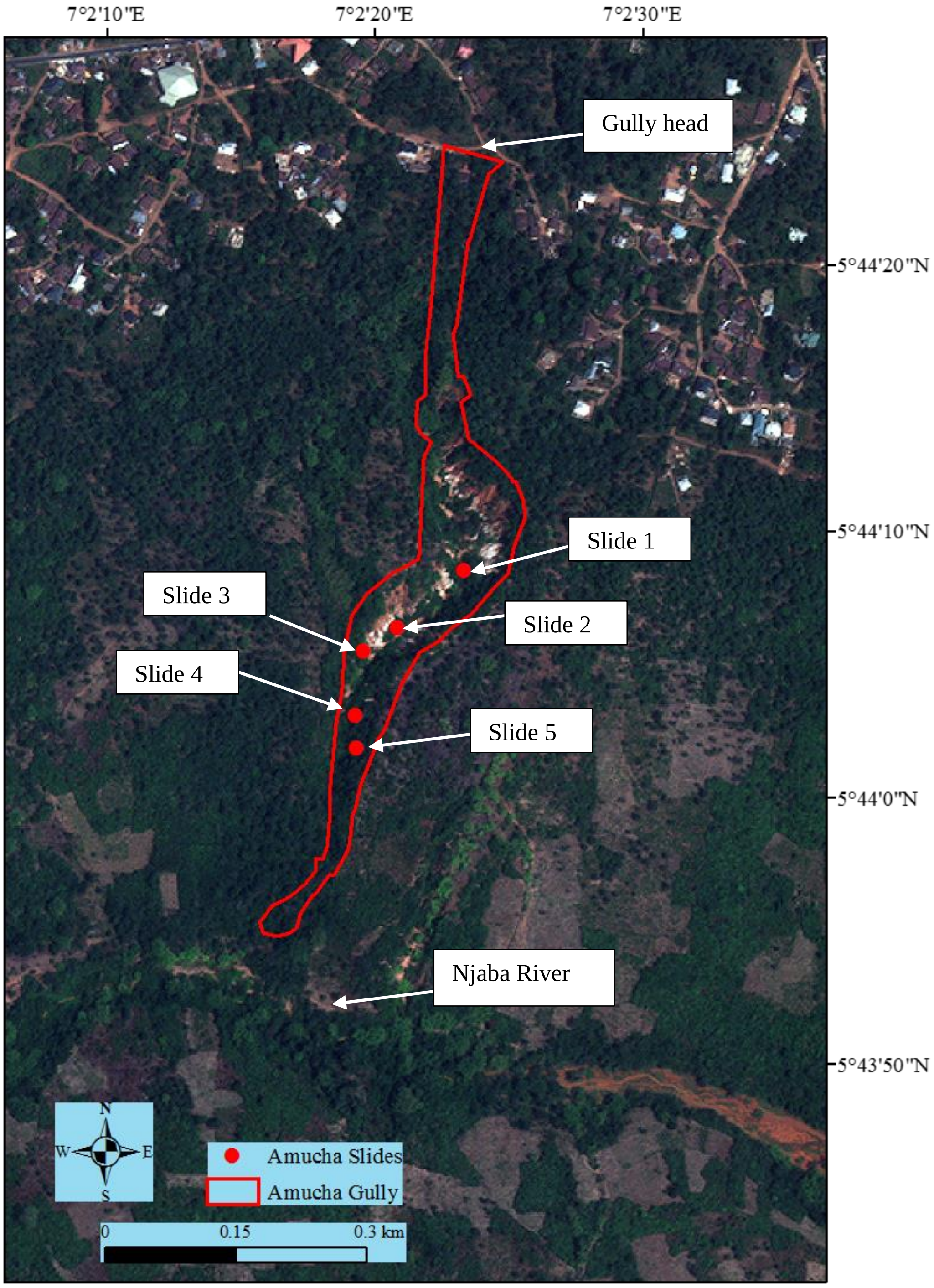

Figure 6.1: Amucha gully draped on the 2017 satellite imagery showing five fresh landslide sites described in Table 6.1. The Njaba River is also shown.

6.1.1 Sensitivity analysis and slope stability results

Sensitivity analysis was undertaken to understand the strengths and contributions of the individual parameters (e.g. slope angle) defined by the slope stability equation (section 3.2.3.3) and thereby make informed decisions about management practices. Landslides in the gullies were more sensitive to changes in slope angles (β) and depth of material (z). All other variables held constant, slope failure within the gullies is likely to occur as the slope angle and depth of material approach 32° and 2.5 m respectively (figure 6.3).

Table 6.1: Identified gully-induced landslides in the Amucha gully.

Slide name	Coordinates	Slope angle (°)	Description
Slide 1	05.73569N 007.03989E		Complex slide – This landslide is complex having three simultaneous failures. All slides were shallow debris slides with short runout distances between 7.7 – 15 m.
First slide		25	
Second slide		30	
Third		38	
Slide 2	05.73509N 007.03920E	32	Presence of slumping mass. Presence of multiple failures.
Slide 3	05.73484N 007.03885E	25	Shallow debris slides
Slide 4	05.73418N 007.03877E	34	Shallow debris slide
Slide 5	05.73384N 007.03878E	22	Shallow debris slide

Modelled FoS is greater than 1 at all the visited slides in the Amucha gully (figure 6.4), and hence, the slopes are not expected to fail again. Considering these slopes have already failed prior to fieldwork may be a possible reason for greater than 1 FoS. If the vertical thickness of materials (depth) is 2.5 m, and at a slope angle of 32°, failure is likely to occur (figure 6.3), thus, another possible reason for higher than 1 value of FoS is because the vertical thickness of materials was perhaps less than 2.5 m at these visited slides. Sustained reduction in the FoS as the slope angle of the gully walls increased was identified (Figure 6.4), and this information is similar to that shown in figure 6.3A; as gully walls attain steeper slope angles, susceptibility to gully-induced slides increase.

Figure 6.2: Gully-induced slide showing multiple failures within the Amucha gully (slide 1 of Table 6.2), location: 05.73569N, 007.03989E.

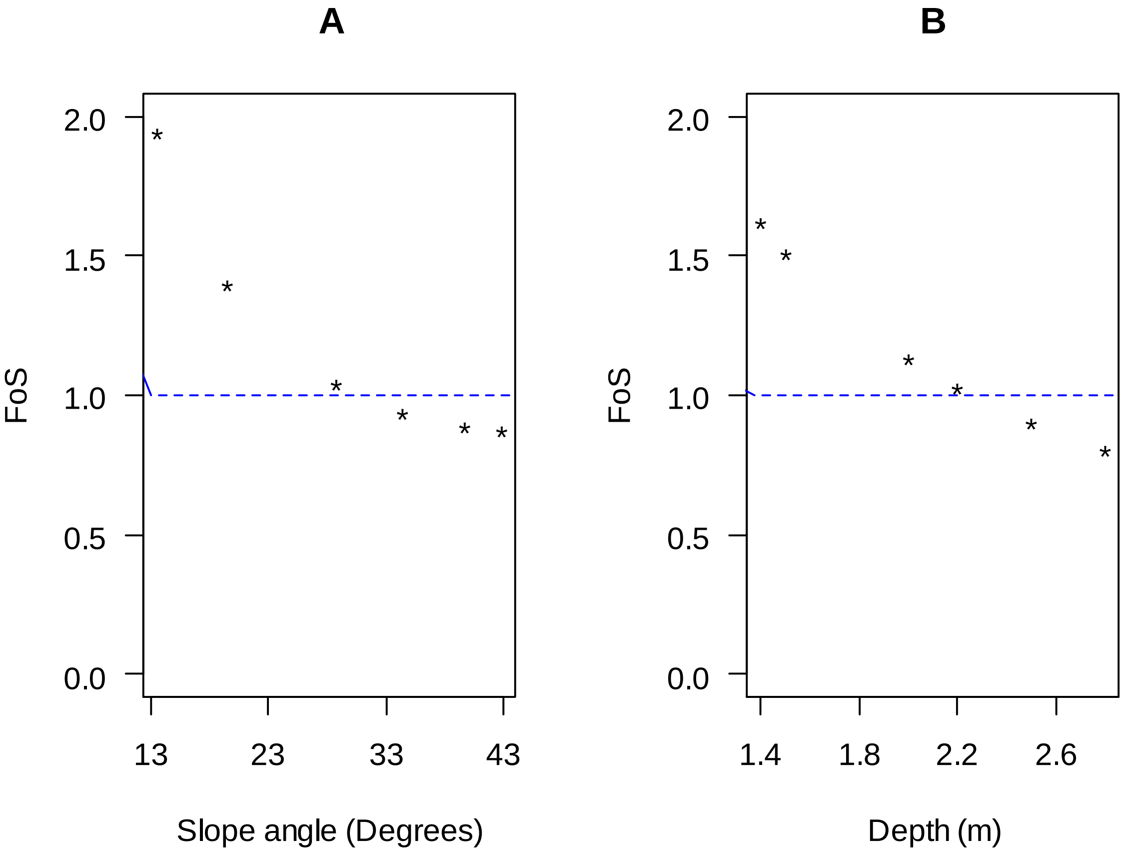

Figure 6.3: Sensitivity analysis showing relationships between: A) FoS vs slope angle, and B) FoS vs depth of material. Blue dashed lines show threshold FoS value beyond which landslides are likely to occur. Slope values in A, are from two gullies captured during drone survey in Urualla. Gully-induced slides will probably happen when the slope angle and vertical thickness advance towards 32° and 2.5 m respectively, if all other variables are held constant.

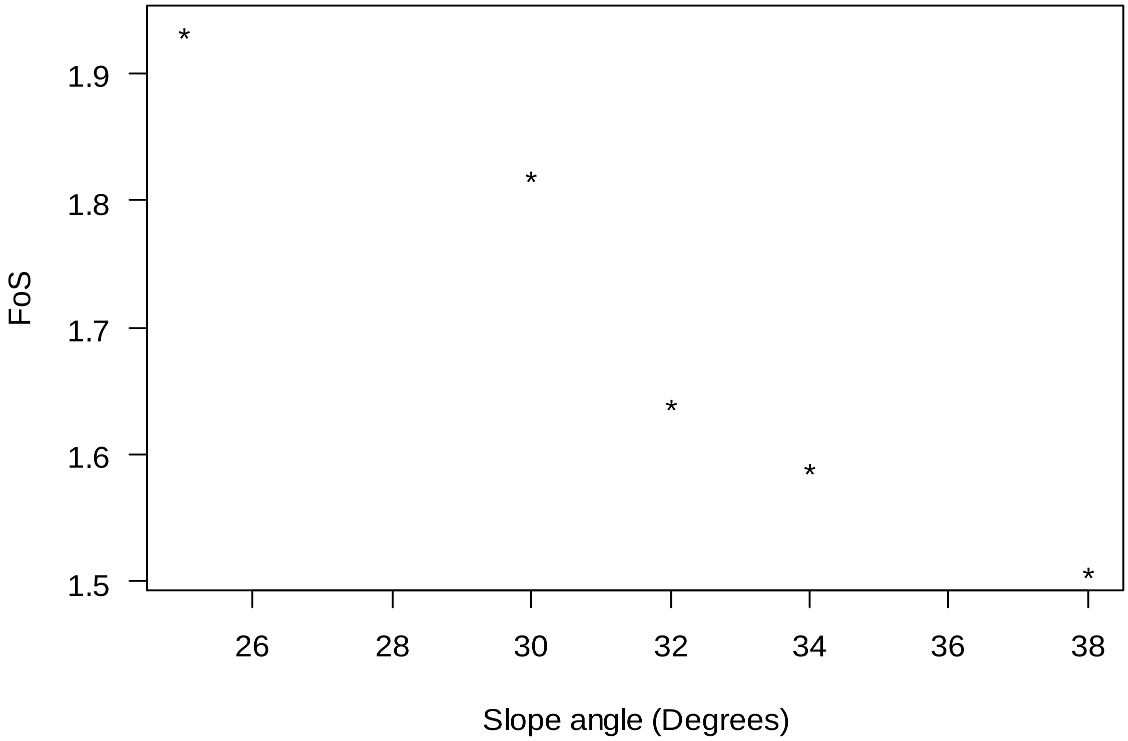

Figure 6.4: Stability analysis for landslides at the Amucha gully showing greater than 1 FoS values. The slopes had already failed prior to site visit, this condition could explain why the FoS values are greater than 1.

6.1.2 Conceptual model of gully expansion by landsliding

Observations from fieldwork suggest that three processes of gully expansion by landsliding occur in the area: soil fall, block failure and shallow debris slides. Shallow debris slides were seen in Amucha and the older gully in Obibi-Ochasi, block failures were observed in Isu Njaba and the younger Obibi-Ochasi gully. Although sliding was noticed in the Urualla and Umueshi gullies, both sites have experienced engineering interventions. The three landsliding processes observed in the study area can lead to lateral expansion of gullies and are discussed using a conceptual model.

Soil fall: Some sections of the younger gully in Obibi-Ochasi exhibited this type of failure. As seen in the field, this process involves a bottom–top mechanism of failure and three stages can be distinguished. First, in a gully whose walls are near vertical and the gully top (surface surrounding the top of the gully) is either vegetated or non-vegetated, surface runoff flows into the gully from upstream areas; surface runoff flowing through the gully floor gradually but steadily erodes the gully bottom walls. This stage is detachment-limited and eroded materials are transported so the walls at the base have no protection (Figures 6.5 A, B). This process continues until a time when the hanging unconsolidated soil material fails due to gravity or increase in self-weight due to addition of moisture. Initially, there is transport-limitation due to the volume of failed slope materials, so that at this stage, the freshly failed materials provide toe-shield to the wall of the gully floor, and thus, surface runoff does not immediately erode the gully wall (Figures 6.5C and 6.6 A,B). With subsequent rains in the wet season, the deposited material will be carried downstream, thereby the process of wall erosion at the base starts again. After the initial failure, the hanging wall directly above the freshly failed material begins to show signs of instability (in forms of tension cracks) due to removal of basal support, (Figures 6.5C, figure 6.6A). These tension cracks sometimes run from the gully top to the bottom. They can also transport surface runoff from the top of the gully to the bottom in a vertical direction or enhance infiltration into the gully wall. Both processes can facilitate instability either through erosion by surface runoff flowing vertically to the gully floor or through increase in weight of slope materials due to addition of moisture or increase in pore pressure due to infiltration (Akpan, et al. 2015). After some time, again due to gravity, or increased self-weight due to addition of moisture, or transmission of kinetic energy from trees on gully top, or tree weight (Greenway, 1987), this last hanging wall fails, thereby expanding the gully width.

Block failure: A process of gully expansion observed in the Isu gully is block failure. Some sections of the younger Obibi-Ochasi gully also showed signs of this process of sliding. Fieldwork observations show that this method occurs by the detachment of blocks of soil by combined actions of tension cracks and sustained erosion by water flowing through such cracks. As tension cracks form, they convey water to gully floors from the top. As this process of conveying water continues, there is continuous erosion and expansion of the tension cracks (figure 6.8A, B), until such a time when a part of the soil block is substantially detached from the rest of the gully wall. At this point, the soil block falls off in the form of block failure (figure 6.8C). The difference between soil fall and block failure as observed in the field is that soil fall starts from the gully floor and erodes upwards in a bottom-top formula, and failure occurs in the form of debris/soil fall. On the other hand, gully block failure starts from the top and failure occurs as a topple or block failure. While there is a remaining block of material (hanging wall) above the failed scar in soil fall, there is none left after block failure.

Shallow debris slide: this type of landsliding was identified in Amucha (figure 6.2) and in the older gully in Obibi-Ochasi. Unlike the other two processes described above which were found in near-vertical gully walls, shallow debris sides were observed in less steep-wall sections of the Amucha and the older Obibi-Ochasi gully. Both gullies were the oldest in the study area. There was scanty vegetal cover at slide sites in both cases. The following processes likely enhance debris slides. Scanty or non-vegetal cover can possibly enhance rill incision by surface runoff as observed at Amucha landslide site 2 (picture not shown), when the rill walls pass a critical slope angle, slope failure can occur (Betts et al. 2003) thereby encouraging landslide-enhanced gully expansion. Also, the vegetated nature of the gully tops (surrounding areas around both gullies were vegetated) may possibly lead to higher infiltration of water into the gully slopes thereby increasing the effect of pore water pressure as a driver of slope failure. Increased weight of rainwater and trees on gully top can also reduce slope stability (Greenway, 1987).

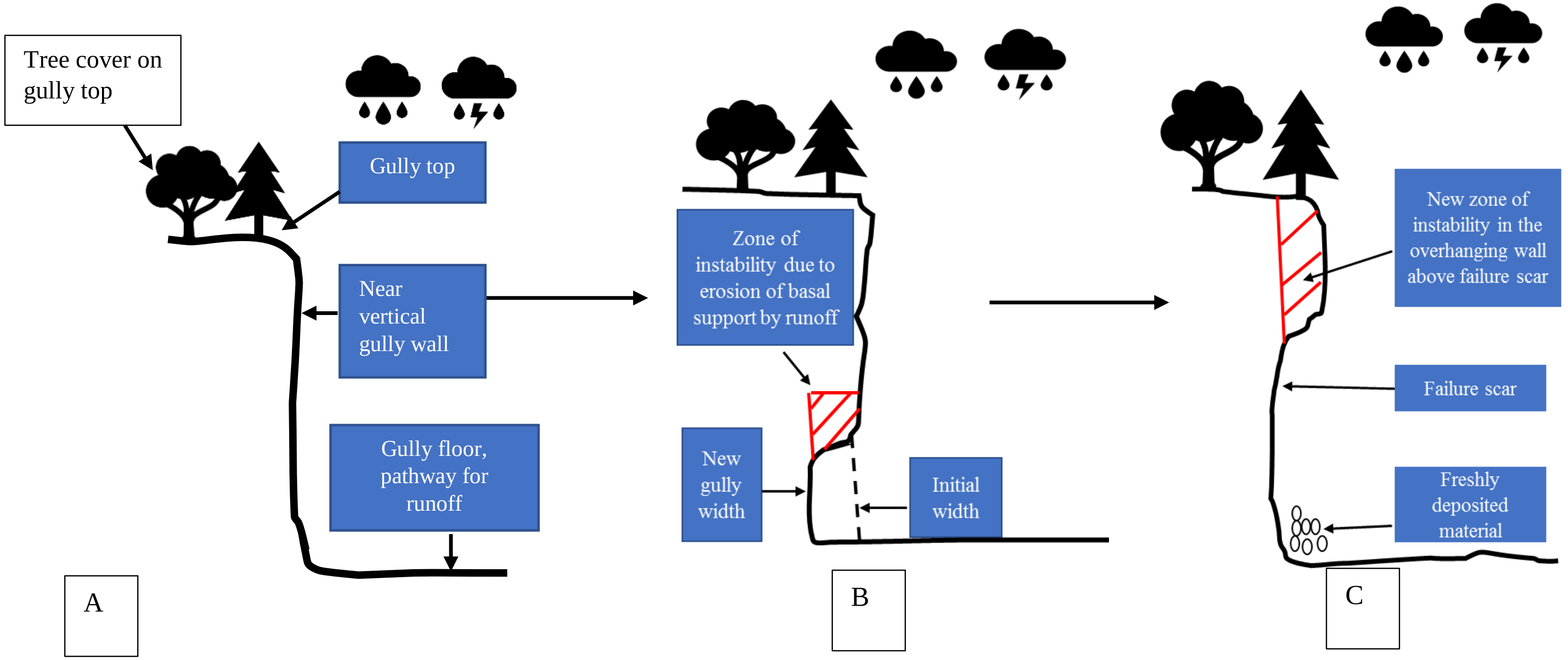

Figure 6.5: A) Near vertical gully wall. Also shown is gully floor, pathway of runoff, B) As runoff flows through the floor, there is gradual but steady erosion of gully wall at the base. Black dotted lines show the original width of the gully floor, new width of gully at the base is also shown. The hatched red box represents a zone of instability caused by the erosion of gully wall at the base by runoff. Tension cracks develop due to instability. Eroded material is transported immediately by runoff, thus, there is no gully toe shield due to this detachment-limited process. C) Momentary transport-limitation due to the volume of failed material, and therefore, the base of the gully wall is briefly protected from further surface runoff erosion. The hanging wall above the failed scar becomes another part of the gully experiencing instability due to removal of basal support.

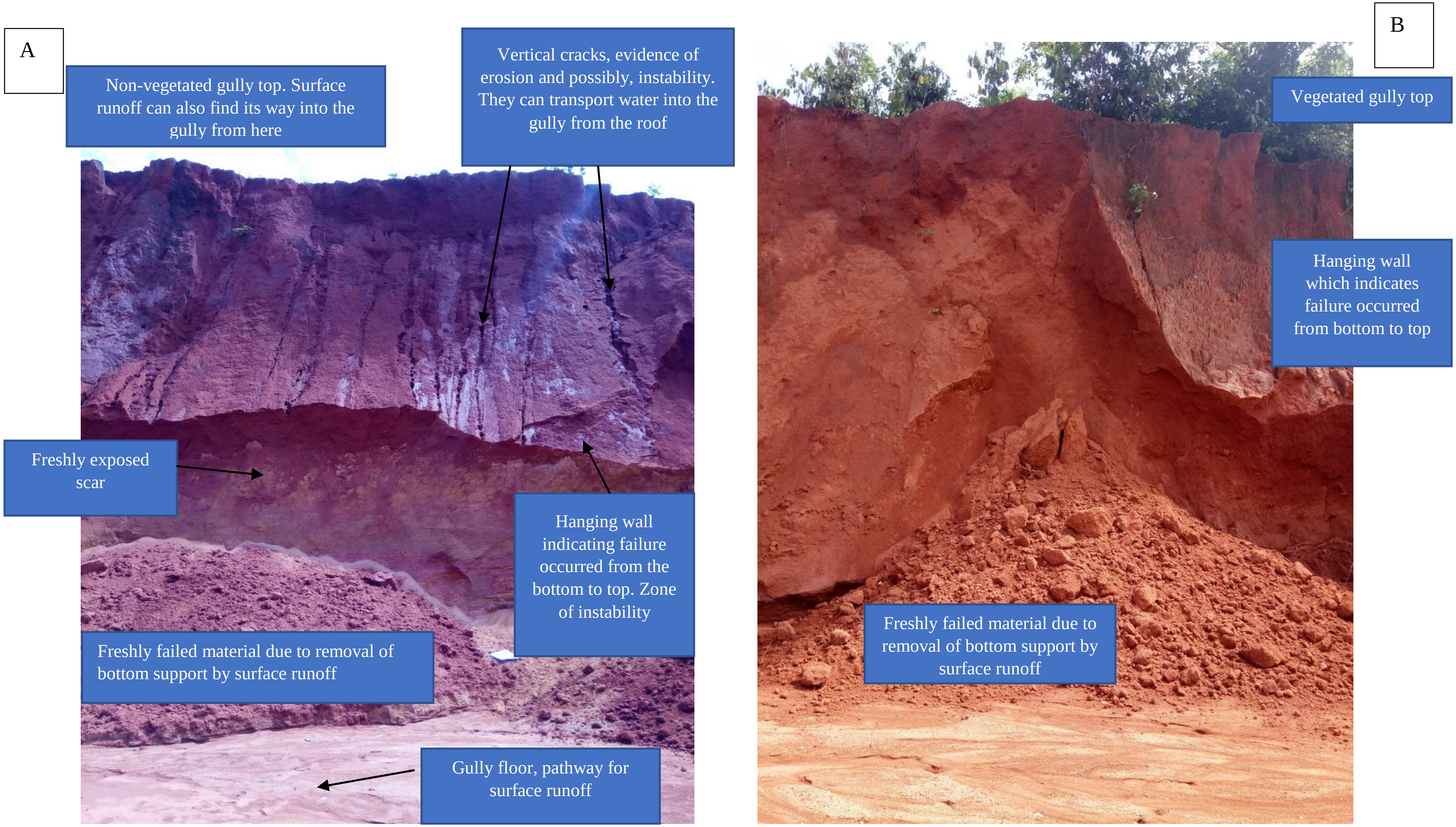

Figure 6.6: Gully expansion caused by soil fall, a bottom–top process of gully-induced landsliding. The hanging wall is a zone of instability due to removal of toe-support. For a moment, freshly failed materials will protect gully base from further erosion by surface runoff. Location: Younger gully in Obibi-Ochasi, Orlu LGA.

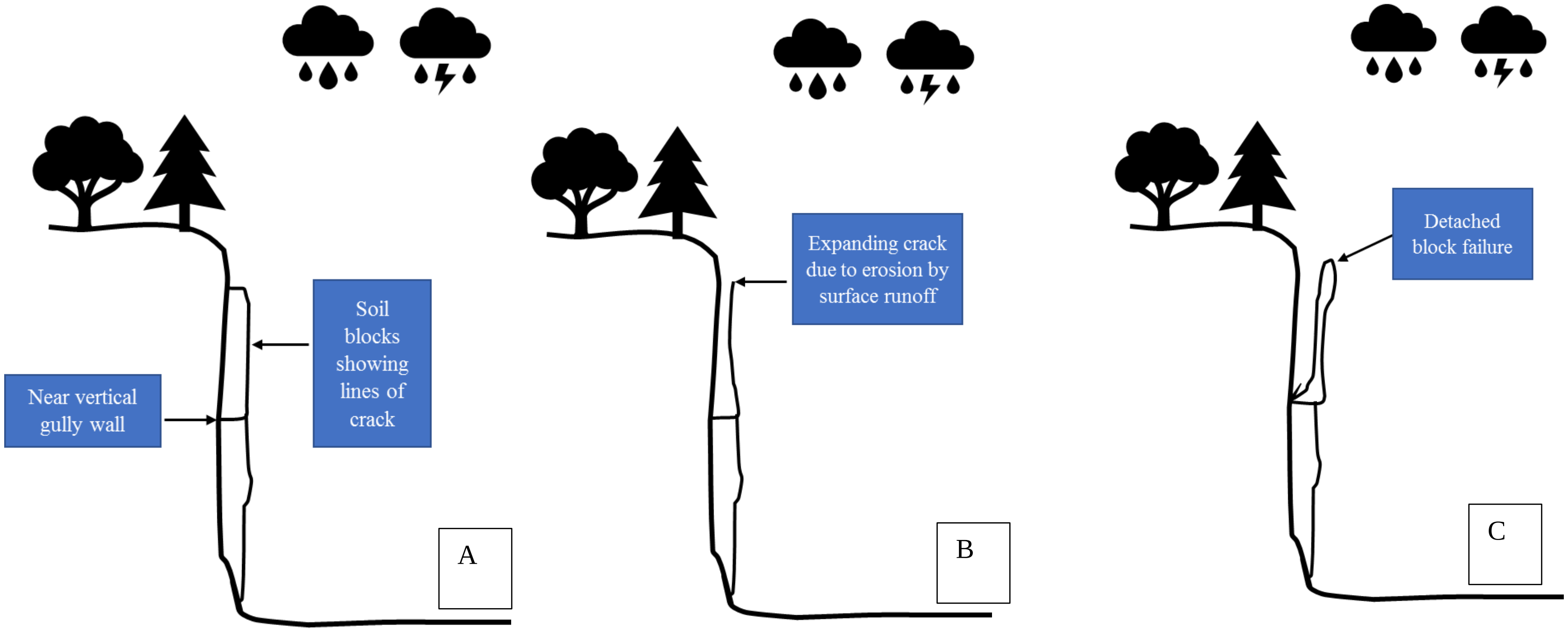

Figure 6.7: A) Development of vertical/diagonal cracks on the gully wall, B, overtime, cracks expand as a result of erosion by surface runoff flowing into cracks from gully top. C, Blocks subsequently detach completely from main gully wall and fall like topples/block falls. This type of failure starts from the top.

Figure 6.8: A) Block detachment in progress as evident in the size of tension cracks. B) Gully expansion caused by block failure, a top–bottom process of gully-induced landsliding. Location: Younger gully in Obibi-Ochasi, Orlu LGA.

6.2 Land-use changes and gully-landslide interactions

Results in section 5.1.2 suggest that gully catchment hydrology responds to ecogeomorphic activities, especially those driven by changes in land use. For example, in the Amucha gully where debris slides were noticed, sustained reductions in vegetated surfaces were observed in the catchment and increased surface flow was modelled between 2009 and 2018. Also, high volume of lateral flow was modelled in the gully-sub-basins (Appendix 5.2) while average gully width increased by 13 m (Table 5.7). Although the upstream sub-basins experienced reductions in fallow, the areas surrounded the gully top were vegetated which might enhance infiltration into the gully slopes. Increase in weight of gully slope materials likely facilitate debris slide. Deposited materials from debris slides will be transported away from gully bottom by ephemeral flows observed during fieldwork. Higher surface runoff from upstream reaches of the catchment increase the volume of ephemeral flows, and thereby enhancing faster removal of toe support.

In Isu Njaba where block failure was observed (Isu_gully1, Table 5.6), a 4 m reduction in average gully width was observed between 2009 and 2014 while increase in average width of 12 m was recorded between 2014 and 2018. Continuous reduction in fallow and increased surface runoff values were modelled in this catchment. Higher lateral flow values were modelled in gully-adjacent sub-basins (Appendix 5.6). Increase in widths were observed in the Urualla and Umueshi gullies corresponding to reduction in fallow, however, these gullies have received engineering interventions. Based on field observations and modelled results, effects of land-use changes on gully-landslide interactions could be explained under two headings:

1) Increased surface runoff due to higher non-vegetated cover and reduction in tree/fallow-cover
2) Higher sub-surface flow as a result of increase in tree/fallow-cover

Increased surface runoff: Section 6.12 presented a conceptual model for gully expansion by landsliding. Higher runoff volumes caused by increased non-vegetated surfaces will influence gully-landslide interactions in the following ways:

a. With regards to soil fall, higher volume of runoff flowing through a gully will increase the rate of gully wall erosion at the gully base and likely increase in failure frequency of material above the zone of instability (as identified in figures 6.5 and 6.6).

b. There will be faster removal of failed material (from block, soil and debris failures) which provides toe support at gully base and this process exposes gully walls to a fresh cycle of erosion by surface runoff.

c. There will be an increase in volume of runoff flowing through vertical cracks with the potential to widen the vertical cracks and increase detachment of soil blocks from main gully walls.

d. Bare and rough surfaces created by debris slides (for example, figure 6.9) could lead to formation of rills and channels for surface flow thereby enhancing landslide-induced gully expansion through these rills.

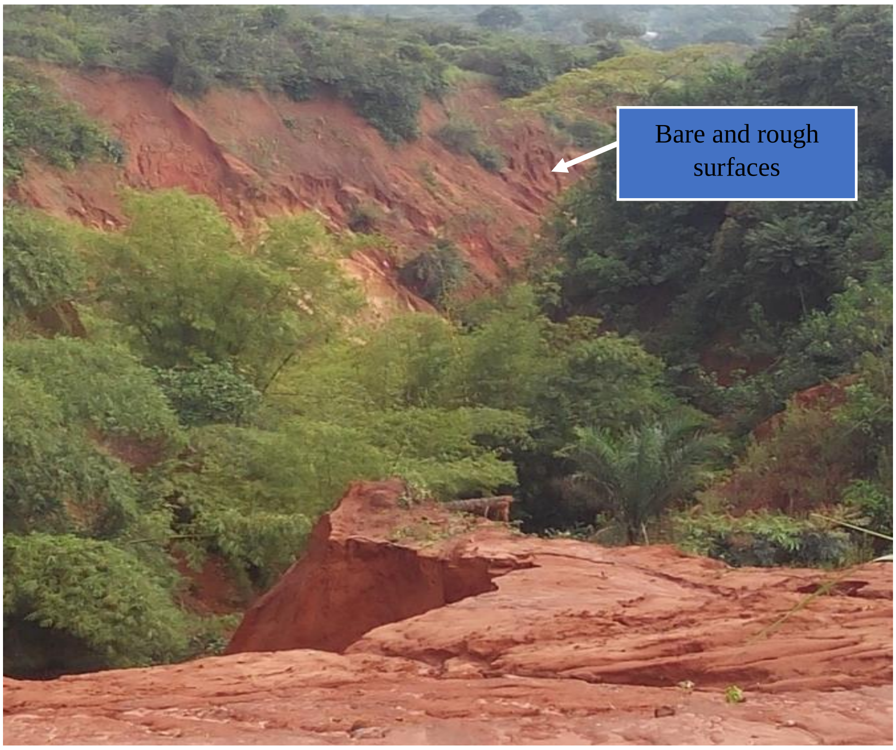

Figure 6.9: Gully site showing presence of bare and rough surfaces which can serve as surface runoff channels. Location: Umueshi, Ideato South LGA, Imo State (photo captured in April 2016).

Higher sub-surface flow: enhanced infiltration due to higher vegetal cover can lead to higher occurrence of gully-induced landslides in the following ways:

a. With regards to soil fall, the response time for hanging wall collapse will likely be reduced. The conceptual model of gully-induced landslides described above suggests that higher vegetal cover on the top of the gully will increase the self-weight of slope materials through enhanced infiltration or extra weight from trees. Thus, increased vegetal cover will possibly reduce lapse time for hanging wall collapse due to extra weight of slope materials caused by higher moisture content.

b. Elevated pore water pressure may enhance slope failure (section 2.2.1).

c. Increased susceptibility to sliding due to sub-surface flow. Presence of springs (indicative of sub-surface erosional activities) were observed at both the Obibi-Ochasi and Amucha gullies. Modelled results for both gully catchments shows substantial groundwater and lateral flows respectively for 2009 and 2018 (figure 6.10).

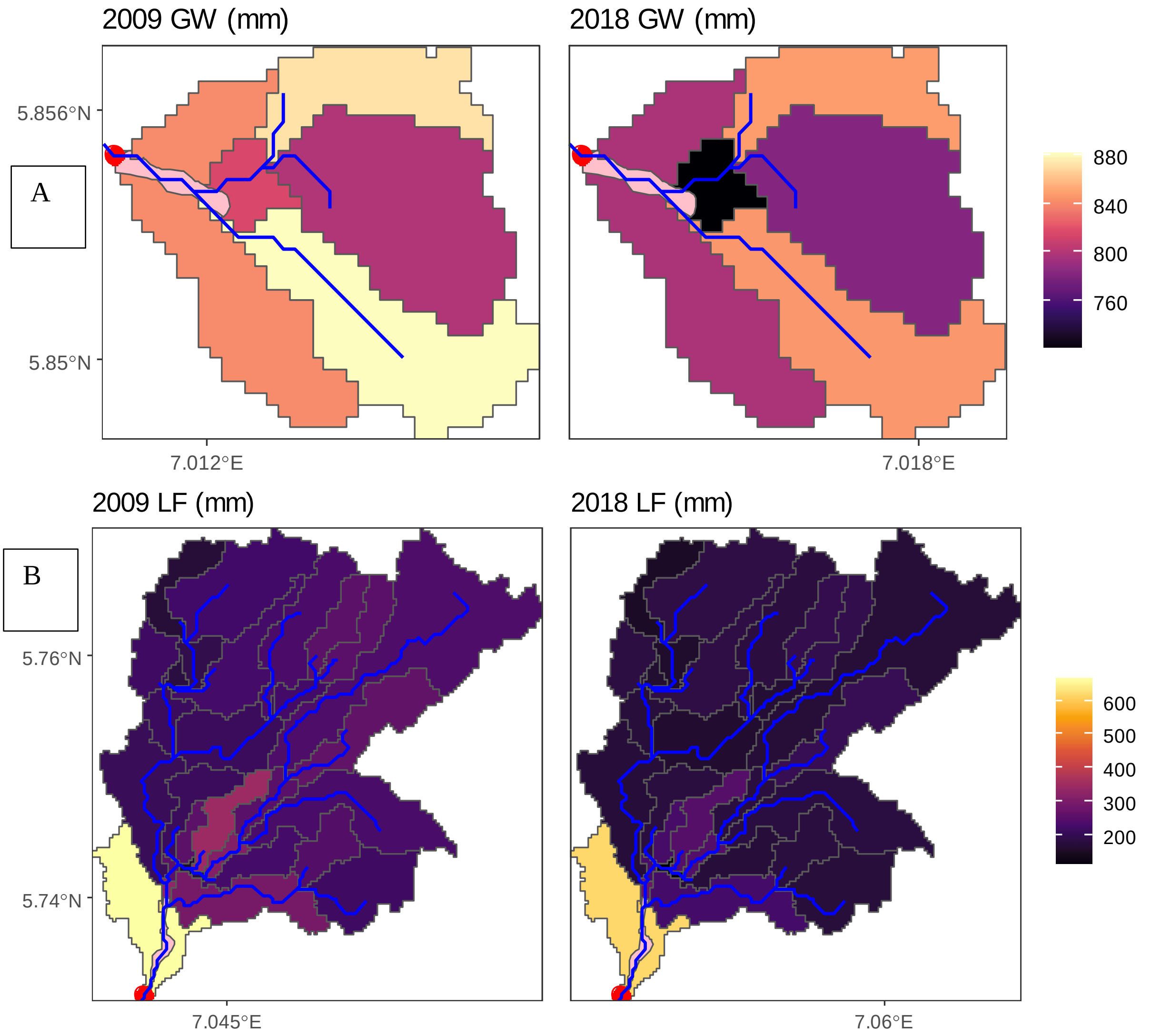

Figure 6.10: Substantial volumes of sub-surface flows modelled at A) Obibi-Ochasi, B) Amucha gully-sub-basins. GW = Groundwater, LF = Lateral flow.

6.3 Discussion

6.3.1 Gully-induced landslides

The factor of safety results shown in figure 6.4 indicate that the slopes of visited gully sites are not likely to fail as they were above 1 in all cases. Maduka et al (2017) obtained an FoS of 1.45 for the Nsukka area of southeast Nigeria, their study area had a higher sand content similar to the Orlu area under investigation in this study (particle-size distribution results of study area is shown in Table 4.13). They suggested that FoS of 1.45 indicated that the slope is moderately stable but not at a safe level required. They went further to propose that an FoS of 1.5 is the value for satisfactory stability. Judging from figure 6.4, the lowest FoS is 1.5, and one could cautiously say, that due to the already failed state of the slopes, the gully walls at the visited sites are satisfactorily stable, all other conditions being equal.

With regards to gully-induced landslides observed during fieldwork, soil and block falls were found in near vertical "U"- shaped gully walls (e.g. younger gully in Obibi-Ochasi) shown in figures 6.6 while debris slides occur in "V"- shaped less steep walled gullies (e.g. Amucha gully, figure 6.2). Focus group meetings showed that the Amucha gully started in 1969, while the younger gully in Obibi-Ochasi (figure 6.6) started less than two years from the date of fieldwork (May 2019). A comparison of both gullies based on likely processes of lateral expansion and substituting space for time, it seems likely that gully expansion by soil fall will probably continue as long as streamflow through the gully has enough energy to erode the bottom walls of the gully. As the gully expands and required erosive energy of surface runoff diminishes, block fall will potentially become the dominant method of gully-induced slides. Block falls accompanied by reductions in erosive power of surface runoff will possibly lead to a transport-limited condition, thus, the gully will recline into a "V"- shape, thereby, debris slide will take over as the dominant process of gully-induced landsliding. When the gully attains a near-permanent transport-limited stage, vegetation colonisation could occur, thus, gradual stabilization will likely set in. It is this gradual stabilisation that will give the gully a "V"- shape with less steep slopes. Younger gullies (figures 6.6 and 6.8) therefore will be more likely to experience gully expansion by soil and block failure while older gullies (figure 6.2) will more likely experience width expansion by debris slides.

6.3.2 Sub-surface flow as an agent of gully-induced sliding

Groundwater, a component of sub-surface flow, has been identified as a driver of gully-induced landslides which involve removal of earth materials in larger volumes (Okagbue & Uma, 1987). Groundwater can enhance gully expansion through slumping (Tebebu et al.0ol 2010), slumping was observed at one of the slide sites in the Amucha gully. Results from focus group meeting and interviews suggest that gully-induced landslides in the area do not occur during rainfall events. In the words of respondents, "despite the intensity of rainfall, you will not find sliding occurring, but after a day or two, you see the soil falling". Groundwater estimates for 15-days rainfall events in 2009 in the Amucha catchment between the 126th to 140th days of the year show the effect of cumulative rainfall on groundwater flow. For example, 57.2 mm of rain fell on the 126th day, whereas same day had the least estimate of groundwater flow (0.3 mm). Highest groundwater flow was estimated on the 140th day of the year, yet no rainfall occurred on that day or the previous day (figure 6.11). The point being made here is that the cumulative effect of rainfall is very important as a driver gully-induced sliding and not just the wettest rainfall events.

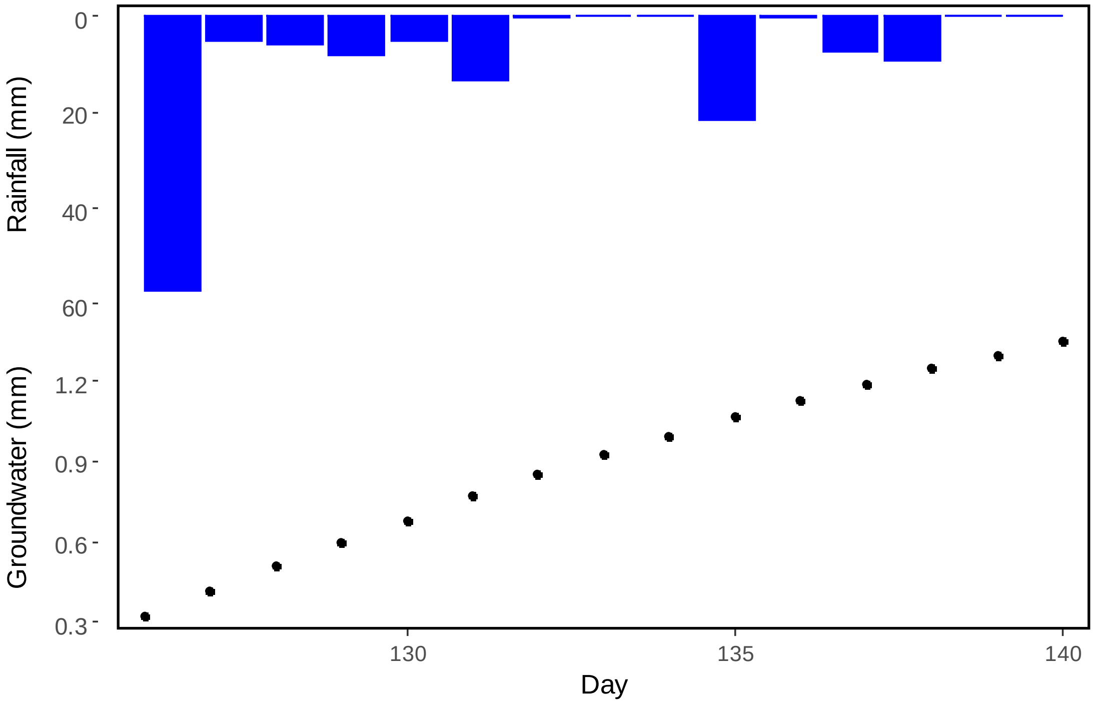

***Figure 6.11:** 15 days rainfall/groundwater flow estimates for 2009 in the Amucha catchment. There is a lag between highest rainfall and highest groundwater flow and thus points to the effect of cumulative rainfall on groundwater.*

The observation from focus group meetings and interviews regarding the lag between rainfall and landsliding points to the possible control of sub-surface flow as a gully-induced landslide-driver in the visited communities and similar reports have been documented in other parts of southeast Nigeria (e.g. Eze, 2007; Igwe, et al. 2013; Emeh and Igwe 2017). Evidence of groundwater-driven landsliding include presence of springs at landslide sites. During fieldwork, springs were observed in some of the visited gullies (older gully in Obibi-Ochasi and Amucha), suggestive of groundwater-driven gully-induced sliding.

Another component of sub-surface erosion which can enhance gully-induced landsliding is seepage erosion. Regarding gully-induced landslides, seepage erosion can affect slope stability in three ways (Egboka & Nwankwor, 1985; Okagbue & Uma, 1987; Dunne, 1990; Fox & Wilson, 2010):

a. Increase in pore-water pressure especially during the peak recharge times of the rainy season can reduce the effective strength of the unconsolidated materials along the seepage faces. In soils with less permeable clay layers, the clay materials are also lubricated and saturated with groundwater. The clays subsequently expand and lose their shear strength due to the excess pore-water pressure thus resulting in slope failure. Pore-water pressure can also be increased during the collapse of tunnel/pipe roofs due to obstruction and subsequent build-up of sub-surface flow through the tunnel.
b. Slope undercutting when seepage exfiltrates from the bank and liquefies the soil at the exfiltration point (seepage erosion by particle mobilization).
c. Increasing the hydraulic gradient forces at various levels of seepage on the gully walls thus producing piping and internal erosion that undermine the bases and partial bases of the gullies.

Slope angle influences lateral flow (section 5.1). Therefore, ecogeomophic activities in the form of tree-planting within catchments with high slope angles will enhance lateral flow and likely facilitate the role of seepage erosion in destabilizing gully slopes. Despite higher vegetation cover at gully tops, landslides found on gully walls were sparsely vegetated as vegetation was likely removed during sliding (e.g. Amucha, figure 6.2 and Umueshi, figure 6.9). With regards to surface runoff, there is little or no resistance to surface runoff due to the sparse vegetal cover on landslide sites, and this condition can likely lead to incision and rills, thereby encouraging landslide-induced gully expansion. Fieldwork showed that local drainage channels (figure 6.12) in some communities were routed into the gullies hence, the entire gully floor turns into a fast-flowing stream after rains, thereby removing toe support of failed materials. Figure 6.13 shows evidence of streamflow on the gully floor in some visited gullies. All these conditions occurring simultaneously on a gully site can increase susceptibility to gully-induced sliding.

6.3.3 Land-use changes and gully-landslide interactions

Changes in land use, especially, increase in tree/fallow cover can have mechanical and hydrological effects on gully slopes and by extension, gully-induced landsliding. Mechanically, trees can transmit kinetic energy from wind into slopes and this energy has the capacity to reduce shear strength of gully slopes, thereby increasing their susceptibility to gully-induced landsliding (Greenway, 1987). Tree roots can provide anchorage for slope materials (Stokes et al. 2008) thereby increasing cohesion. Tree-weight can add to the self-weight of soil materials and thereby increasing susceptibility to gully-induced landsliding (Greenway, 1987, Akpan et al. 2015). Hydrological effects of trees on gully slopes include moisture extraction from soil by tree roots. Modelling results presented in section 5.1.2 suggest that substantial amount of water is lost to evapotranspiration from all catchments. Evapotranspiration reduces ground water level which is an agent of gully-induced landsliding (Okagbue & Uma, 1987). However, evapotranspiration from trees might have a limited effect under a tropical precipitation regime, where soils are often saturated (Broeckx et al. 2019). Leaves can intercept precipitation and initiate evaporation reducing available water for infiltration (Greenway, 1987). Surrounding areas on the top of gullies were vegetated at visited gullies except in Urualla and the younger gully in Obibi-Ochasi. Effects of enhanced infiltration, tree weight and transmission of kinetic energy on slope stability will be higher in the vegetated gullies than the Urualla gully.

Two types of land-use changes were observed in section 5.2, increased tree/fallow cover which led to higher sub-surface flow and increased non-vegetated areas which resulted in higher estimates of surface runoff. In catchments/sub-basins that have experienced higher tree/fallow cover during the study period, there was estimated increase in sub-surface flow (figure 5.17). Therefore, gully-landslide interactions are affected by these land use and hydrological changes in the following ways:

a. Higher possibility of sub-surface flow-driven gully-induced landslides.
b. Increased transmission of kinetic energy from trees into gully slopes, a situation that will lead to reduced shear strength of gully slopes and higher susceptibility to gully-induced landslides.
c. Increased weight of soil due to higher infiltration and weight of trees which will likely enhance sliding.
d. Increased cohesion of soil particles on gully slopes due to binding effect of tree roots and a subsequent reduction in susceptibility to gully-induced slope failure. This

condition will be effective only where the tree roots are deeper than the shear surface (Okagbue & Uma, 1987).

e. Reduced groundwater levels due to evapotranspiration from gully walls thereby reducing susceptibility of gully slopes to groundwater-driven slope failure.
f. Rain interception by tree leaves and subsequent evaporation thus reducing available water for infiltration.

In catchments where increases in non-vegetated surfaces were observed and higher surface runoff volumes modelled, gully-landslide interactions are affected in the following ways:

a. Increased erosion of gully walls at the gully floor. This situation increases frequency of failure of hanging wall and gully expansion by soil fall.
b. Higher rate of removal of toe support; thus, reducing the relaxation time between toe-protection and another cycle of toe erosion and eventually leading to higher gully widening rate.
c. Increased rill expansion rate on landslide scars which in turn facilitates landslide-induced gully widening. This condition is enhanced by the bare nature of landslide scars.

Figure 6.12: Human-made structure and natural rills deliver surface runoff directly into gullies. A) Obibi-Ochasi Gully2. B) Umueshi Gully. Concentrated runoff flowing on gully floors can remove toe support at landslide sites, hence, enhancing slope failure. Natural rills found close to gullies had depth ranges between 0.4 – 0.7 m, widths varied between 0.25 & 2.2 m while lengths ranged from 10 – 60 m.

Figure 6.13: Evidence of streamflow on gully floors at the younger Obibi-Ochasi gully. Also shown is a destroyed drainage structure designed to transport runoff to a local base level.

6.4 Chapter summary

The aim of this chapter was to understand effects of changes in land use and gully catchment hydrology on gully-landslide interactions. Gully-induced slides observed in the study area can take three forms: soil and block failure and debris slide. Field work results shown in section 6.2 supported by previous studies (documented in section 6.3) indicate that all three mechanisms of gully-induced landsliding observed in the field can be affected by changes in land use and hydrology of the gully catchments. So far, it has been suggested that there could be beneficial and detrimental effects on gullies following land use and hydrological changes. For instance, increased tree-cover could reduce erosion of gully walls by surface runoff but increase self-weight of sliding materials. Gully erosion can lead to gully-induced slides while uneven surfaces created by landslide scars could promote formation of rills which might enhance gully expansion by landslide-induced erosion. The phenomenon of gully-induced landslides and landslide-induced gullies can lead to the formation of complex gully systems which pose challenges to gully management.

6.5 Conclusions

The following conclusions are made:

I. Gully-induced landslides is a mechanism of gully expansion identified in the study area. At all visited gullies, at least one of debris slide, soil fall or block failure, was observed. Occurrence of these landslide processes may be driven by gully age.

II. Block failure and soil falls were observed in “U-shaped” sections of gullies while debris slides were seen in “V-shaped” segments of gullies. Based on field observations, it is thought that younger gullies (U-shaped) would experience block and soil falls, while debris slides will occur in older gullies.

III. Despite the vegetated lands on the top of gullies, one form landsliding was observed at all visited gullies. This point suggests that tree-planting alone may not control gullying. It is also likely that enhanced infiltration (due to vegetated gully tops) facilitates destabilization of these gullies.

IV. Modelling results and fieldwork suggest that ecogeomorphic activities, especially, land-use changes can affect gully-landslide interactions.

Chapter 7

Resultant hazards of gully-landslide interactions

7.0 Introduction

Chapter 7 provides answers to research questions raised by objective 4 (to determine resultant hazards posed by gully-landslide interactions). The following research questions are posed:

1. What is the perception of local population to gully-landslide hazards?
2. What are the effects of gully-landslide interactions on affected communities?
3. What control measures have been adopted by communities to reduce effects gully-landslide interactions?

To answer the research questions, results from the three qualitative research approaches adopted in this study: use of structured questionnaire, focus group meetings and oral interviews (section 3.2.4) are presented. A total of 192 copies of questionnaire were distributed to Amucha and Obibi-Ochasi communities, that is, 96 copies per community (section 3.2.4). There were 100% and 73% questionnaire return rates in Amucha and Obibi-Ochasi communities respectively. Four and two copies of questionnaire were not properly filled in Amucha and Obibi-Ochasi respectively, thus, responses from 92 (52 male and 40 female respondents) and 68 (42 male and 26 female respondents) correctly filled questionnaire retrieved from Amucha and Obibi-Ochasi communities, respectively, were used in this study (Table 7.1). In Amucha, 10 responses were received from the older population (≥ 60 years old) while six people from this age-group returned their completed questionnaire in Obibi-Ochasi (Table 7.1). Regarding the younger population (18 – 49 years of age), 68 copies of questionnaire were returned in the Amucha community, while 52 respondents in this age-group completed and retuned their questionnaire in Obibi-Ochasi.

A public document published in 1981 by the Imo State Government (Imo State Government, 1981) stated that gullies in Amucha and Obibi-Ochasi communities gained prominence in the early 1970s, and hence, it was expected that elders (≥ 60 years old) may have been exposed to the gradual change in gully sizes over these years, but especially, in the last 10 years of interest in this study. Based on this document, focus group participants included 9 elders (≥ 60 years old) and one younger person (40 – 50 years old) from both communities. Interviewees were between 35 – 65 years of age.

Section 7.1 shows results on community perception of hazards of gully-landslide interactions and causes of both gully erosion and gully-induced landslides. Section 7.2 presents results on identified effects of these interactions on affected communities. Control measures put in place (either by community effort or external aid) to alleviate problems of gully-landslide interactions are presented in section 7.3. Chapter summary and conclusions are presented in 7.4 and 7.5.

Table 7.1: Breakdown of age-groups and gender of questionnaire respondents.

	Amucha	Obibi-Ochasi
Age	**Sex**	**Sex**
	Male respondents	Male respondents
18-28	6	15
29-39	13	5
40-49	18	9
50-59	8	8
≥60	7	5
Total	52	42
	Female respondents	Female respondents
18-28	8	12
29-39	8	4
40-49	15	7
50-59	6	2
≥60	3	1
Total	40	26

7.1 Community perception of hazards of gully-landslide interactions

Section A of the questionnaire (Appendix 7.1) was used to understand perception of respondents to hazards posed by gully-landslide interactions. Questions 1 and 4 asked respondents if they knew what gully erosion and landslides were respectively, 43 respondents (21 males and 22 females) in Amucha agreed they knew what gully erosion was and 4 respondents have heard about gully erosion but do not know what it is (Table 7.2). In Obibi-Ochasi, all 68 respondents knew what gully erosion was. One female respondent in the age-group of 40 – 49 years chose two options, A (Yes I know what gully erosion is) and C (No, I do not know what gully erosion is) for question 1, hence the total of 69 responses, whereas there were 68 respondents in Obibi-Ochasi (Table 7.2). Three choices were provided for question 4: A) Yes, it is same with gully erosion, B) Yes, I have heard about it but I do not know what it is, C) No idea what landslide is. In Amucha, 84 respondents chose ‘A’, 8 ticked

‘B’, and 2 selected ‘C’. In Obibi-Ochasi, 47 people ticked ‘A’, 20 selected ‘B’ and one respondent chose option C (Table 7.3).

Table 7.2: Responses to question 1: Do you know what gully erosion is? A: Yes I know what gully erosion is. B: Yes, I have heard of gully erosion but I do not know what it is. C. No, I do not know what gully erosion is. D. I have never heard of gully erosion before.

	Amucha				Obibi-Ochasi			
Age (years)	**Sex**				**Sex**			
	Male respondents	A	B	Total	Male respondents	A	C	Total
18-28	6	3	1	4	15	15		15
29-39	13	9	1	10	5	5		5
40-49	18	6	1	7	9	9		9
50-59	8	2		2	8	8		8
≥ 60	7	1		1	5	5		5
Total	52	21	3	24	42	42		42
	Female respondents				Female respondents			
18-28	8	7	1		12	12		12
29-39	8	6			4	4		4
40-49	15	4			7	7	1	8
50-59	6	3			2	2		2
≥ 60	3	2			1	1		1
Total	40	22	1	23	26	26	1	27

Table 7.3: Responses to question 4: Do you know what landslide is? A: Yes, it is the same as gully erosion. B: Yes, I have heard it but I do not know what it is. C. No idea what landslide is.

		Amucha					Obibi-Ochasi			
Age (years)	**Sex**					**Sex**				
	Male respondents	A	B	C	Total	Male respondents	A	B	C	Total
18-28	6	6			6	15	5	10		15
29-39	13	8	3	2	13	5	4	1		5
40-49	18	17	1		18	9	9			9
50-59	8	8			8	8	7	1		8
≥ 60	7	7			7	5	5			5
Total	52	46	4	2	52	42	30	12		42
	Female respondents					Female respondents				
18-28	8	7	2		9	12	3	8		11
29-39	8	8			8	4	4			4
40-49	15	15	1		16	7	7		1	8

50-59	6	5	1		6	2	2			2
≥ 60	3	3			3	1	1			1
Total	40	38	4		42	26	17	8	1	26

Five options were provided to the respondents when asked if they believe that gully erosion and landslide can cause harm (questions 3 and 6 respectively), A) Yes, I strongly believe gullying/landsliding can cause harm, B) Yes, I believe gullying/landsliding can cause harm, C) I do not know, D) No, I strongly believe gullying/landsliding cannot cause harm, E) No, I believe gullying/landsliding cannot cause harm. In Amucha, 75 people chose ‘A’, 26 selected ‘B’ while one respondent each selected options C and D to question 3, and in Obibi-Ochasi, 45 respondents ticked option A, while 24 and 4 people selected options B and C (Table 7.4). With respect to question 6, 80 respondents in Amucha selected option A, 16 selected option B and one chose ‘C’, in Obibi-Ochasi, 47 respondents selected option A, 22 chose ‘B’ while two selected ‘C’ (Table 7.5).

Results shown in Tables 7.2 and 7.3 indicate that a higher proportion of respondents know what gully erosion and landslides are, although landslides were thought to be the same as gully erosion by 88% and 95% of male and female respondents in Amucha. Similar results were found in Obibi-Ochasi where 71% and 65% of male and female respondents believe landslides and gully erosion are the same. All respondents in both communities have heard about gully erosion while one male respondent in Obibi-Ochasi selected both options A and C for question 1. The high level of awareness of gully erosion and landslides is reflected in the perception of the respondents to likely hazards of both processes, for example, 83% and 80% of male and female respondents in Amucha strongly believed that gully erosion can cause harm. One male respondent in Amucha does not know if gullying can cause harm and another male respondent strongly believes no harm can be caused by gullying (Table 7.4). In Obibi-Ochasi, 67% and 65% of male and female respondents strongly believed gullying can cause harm while two male (5%) and two female (8%) respondents do not know if gullying leads to harm (Table 7.4). Regarding landslide hazard-awareness, 85% and 90% of male and female respondents in Amucha strongly believe landslides can cause harm and 67% and 73% of male and female respondents in Obibi-Ochasi strongly believed that landslides lead to harm (Table 7.5). A further breakdown of Tables 7.4 and 7.5 indicate there is strong awareness across the entire age-groups of the potential of gully erosion and landslides to cause harm. Therefore, in both communities, perceptions of inhabitants based on responses from questionnaire survey indicate there is a high level of understanding of hazards posed by gully erosion and landslides regardless of age.

Table 7.4: Responses to question 3: Do you think gullying can cause harm? A) Yes, I strongly believe gullying can cause harm, B) Yes, I believe gullying can cause harm, C) I do not know, D) No, I strongly believe gullying cannot cause harm, E) No, I believe gullying cannot cause harm.

		Amucha					Obibi-Ochasi				
Age (years)	**Sex**										
	Male respondents	A	B	C	D	Total	Male respondents	A	B	C	Total
18-28	6	6				6	15	5	10		15
29-39	13	9	3	1	1	14	5	4		1	5
40-49	18	15	4			19	9	8	1	1	10
50-59	8	8	2			10	8	7	1		8
≥ 60	7	5	4			9	5	4	1		5
Total	52	43	13	1	1	58	42	28	13	2	43
	Female respondents						Female respondents				
18-28	8	5	4			9	12	3	9		12
29-39	8	7	2			9	4	5			5
40-49	15	13	3			16	7	7	1	2	10
50-59	6	4	4			8	2	2			2
≥ 60	3	3				3	1		1		1
Total	40	32	13			45	26	17	11	2	30

Table 7.5: Responses to question 6: Do you think landsliding can cause harm? A) Yes, I strongly believe landsliding can cause harm, B) Yes, I believe landsliding can cause harm, C) I do not know, D) No, I strongly believe landsliding cannot cause harm, E) No, I believe landsliding cannot cause harm.

		Amucha					Obibi-Ochasi			
Age (years)	**Sex**									
	Male respondents	A	B	C	Total	Male respondents	A	B	C	Total
18-28	6	6			6	15	6	9		15
29-39	13	9	4	1	14	5	4	1		5
40-49	18	14	4		18	9	9	1		10
50-59	8	8	1		9	8	6	1	1	8
≥ 60	7	7	1		8	5	3	1	1	5
Total	52	44	10	1	55	42	28	13	2	43
	Female respondents					Female respondents				
18-28	8	8			8	12	3	9		12
29-39	8	7	1		8	4	5			5
40-49	15	14	2		16	7	8			8
50-59	6	4	3		7	2	2			2

≥ 60	3	3			3	1	1			1
Total	40	36	6		42	26	19	9		28

7.1.1 Local knowledge on causes of gully erosion and gully-induced landslides

Questionnaire respondents were asked what they felt caused gully erosion and four options, a) act of the gods, b) farming techniques, c) sand excavation and d) others, were provided. In the Amucha community, one person ticked option ‘A’, four respondents selected ‘B’, 43 chose ‘C’ while 38 respondents wrote down surface runoff as the cause of gully erosion respectively (Table 7.6). In Obibi-Ochasi, option ‘A’ was selected by 15 respondents, one person chose ‘B’, 44 ticked ‘C’ while 10 respondents wrote down surface runoff as the causes of gully erosion accordingly (Table 7.6). With regards to landsliding, four options were also presented as causes of landsliding, a) gully erosion, b) farming techniques, c) sand excavation, d) others. Responses from 73 participants in Amucha identified gully erosion as the cause of landsliding while 29 participants chose sand excavation as the cause of landsliding (Table 7.7). In Obibi-Ochasi, 46 respondents underlined gully erosion while 21 people wrote down soil factor as the causes of landsliding (Table 7.7).

Table 7.6: Responses to question 2: what do you think causes gully erosion? A) Act of the gods B) Farming techniques C) Sand excavation D) Others.

		Amucha						Obibi-Ochasi				
Age	**Sex**						**Sex**					
	Male respondents	A	B	C	D	Total	Male respondents	A	B	C	D	Total
18-28	6		1	5		6	15			15		15
29-39	13		1	3	6	10	5			5		5
40-49	18		1	8	8	17	9	2		6	1	9
50-59	8			2	4	6	8	3	1	1	3	8
≥ 60	7			1	5	6	5	2			3	5
Total	52		3	19	23	45	42	7	1	27	7	42
	Female respondents						Female respondents					
18-28	8	1	1	6	1	9	12	2		9		11
29-39	8			2	6	8	4	2		2	1	5
40-49	15			13	3	16	7	2		6	1	9
50-59	6			1	3	4	2	1			1	2
≥ 60	3			2	2	4	1	1				1
Total	40	1	1	24	15	41	26	8		17	3	28

Table 7.7: Responses to question 5: what do you think causes landsliding? A) Gully erosion B) Farming techniques C) Sand excavation D) Others.

	Amucha						Obibi-Ochasi					
Age	**Sex**						**Sex**					
	Male respondents	A	B	C	D	Total	Male respondents	A	B	C	D	Total
18-28	6	3	1	4		8	15	5			10	15
29-39	13	9	1	2	1	13	5	4			1	5
40-49	18	14	1	6		21	9	7		2	1	10
50-59	8	7		2	1	10	8	8	1	1		10
≥ 60	7	7				7	5	5				5
Total	52	40	3	14	2	59	42	29	1	3	12	45
	Female respondents						Female respondents					
18-28	8	4	1	4		9	12	3			9	12
29-39	8	8				8	4	4		1		5
40-49	15	14		10		24	7	7	1	2		10
50-59	6	4		1	1	6	2	2				2
≥ 60	3	3				3	1	1		1		2
Total	40	33	1	15	1	50	26	17	1	4	9	31

During focus group meetings (Appendix 7.2), participants were asked to identify causes of gully erosion and landsliding. In Amucha, four factors were mentioned as causes of gully erosion; topography, increase in volume of surface runoff, increase in population density during the Nigerian civil war (1966 – 1970) and “weak nature of our soil”. Focus group members continued “we live in an undulating environment, surface runoff from Eziama, Eziachi, Umuowa all run down to our community, and this condition predisposes us to gullying”. Increase in volume of surface runoff was also attributed to land-use changes, especially, changes from vegetated to non-vegetated surfaces. Regarding roofing materials, participants suggested “the use of aluminium/iron roofing sheets in building construction has increased surface runoff because many years ago, thatch roofs were used, and they produced less runoff”.

In Obibi-Ochasi, surface runoff, the civil war, non-implementation of building regulations, sand mining and act of the gods were the points raised as causes of gully erosion. Group meeting attendees suggested that “surface runoff from surrounding communities, e.g. Ogberuru and Ihitte Owerri all flow down to our community before flowing into the gully and thus further destabilizing the gully”. War time activities including digging trenches were also recognised. One attendee said “During the war, the military desecrated our stream by fishing in the stream.

They also killed the holy python, hence, the gully is a way the gods have shown their anger for the desecration of our holy place". With regards to building regulations, participants cited an example of what was applicable in a nearby state where retention pits are mandatory in every compound. They said "these pits would retain surface runoff produced from individual compounds thereby reducing volume of surface runoff that will find its way to the gully".

Regarding gully-induced landslides, focus group participants noted slides occurred after heavy rains but never during the rainfall. In the words of the participants "despite the intensity of rainfall, you will not find sliding occurring, but after a day or two, you see the soil falling". I asked focus group participants in Amucha to differentiate between gully erosion and landslides and they said, "landslides increase gully widths". At the Isu Njaba community, an interviewee mentioned the appearance of cracks (shear surfaces) in the ground prior to any incidence of sliding. Once these cracks are observed, the inhabitants know sliding is imminent. According to the interviewee, appearance of cracks was observed after heavy rainfalls.

Information from Table 7.6 are slightly different in both communities, e.g. while option 'A' got one response in Amucha, 15 respondents in Obibi-Ochasi identified 'A' as possible cause of gullying. This observation does not come as a surprise judging from the response of focus group attendees in Obibi-Ochasi regarding the show of anger by the local deity to the desecration of the village stream by military officers during the war. Act of the gods was not identified during the Amucha group meeting and questionnaire survey suggests this option is not popular among the villagers. Higher number of respondents (43 in Amucha and 44 in Obibi-Ochasi) identified sand mining as the likely cause of gully erosion, while gully erosion had the highest number of responses as the cause of landsliding (73 in Amucha and 46 in Obibi-Ochasi). Within the study area, laterite, locally known as "*aja red*" (red sand) and marine sandstone (white sand) are among the earth materials mined from the borrow pits and sand vendors sell both types of earth materials side by side. These earth materials are sought after by road construction contractors and other private individuals. The sand mining industry is a big employer of labour due to the high demand for the commodities they offer; however, this economic activity increases susceptibility to gully erosion and gully-induced landslides (Igbokwe et al. 2008; Nwachukwu & Eburukevwe, 2013).

Surface runoff, topography and "weak nature of the soil" were identified as drivers of gully erosion. Combined actions of topography and surface runoff as gully drivers are well known (Zevenbergen & Thorne 1987; Poesen et al. 2003; Knapen & Poesen, 2010; Gómez-Gutiérrez et al. 2015) and the susceptibility of soils of southeast Nigeria to dispersion by erosive forces due to their composition has been suggested (Okagbue & Ezechi, 1988; Egboka & Nwankwor 1985; Idowu & Oluwatosin 2008). Incorporating local knowledge in a research provides for comparison of scientific understanding, hypotheses, forecasts and arguments with prevailing local expertise, thus, enriching scientific findings and these issues form part of the public debate model proposed by Callon (1999). Results from both questionnaire and focus group meetings on gully drivers are in agreement with studies by researchers from different parts of the world. With regards to gully-induced landslides, 46 and 73 respondents in Obibi-Ochasi and Amucha, respectively believe gully erosion is the cause of sliding (Table 7.7). Interview and focus group meetings respondents informed me that landslides only occur a day or two after rainfalls. This result points to the likely effect of groundwater as a driver of landsliding because landsliding may become active up to several days after a large rainfall event due to the time it takes for rainwater to reach the groundwater store (Betts et al. 2003). Modelling results (figure 6.11) suggest there is a lag between highest rainfall and highest groundwater flow while focus group attendees attested to the lag between rainfall and gully-induced landslides. These observations support the notion of groundwater effect as a potential landslide-driver in the study area.

7.2 Effects of gully-landslide interactions on affected communities

Several themes emerged from the data, which are addressed in turn. First, destruction of roads was one of the most common effect of gullying identified in the study area. In Umeshi for example, a community road linking Umueshi and other neighbouring communities had been destroyed as at the time of site visit (figures 4.12C). An interviewee reported that he drove past this road in January 2019 but on May 18 2019 when we visited for fieldwork, it was impossible to connect neighbouring communities using this road. We (I and two field assistants) had to seek alternative routes which were longer. Longer routes are more time consuming and require more fuel supply, thus, there are financial and environmental outcomes of using longer routes due to road destruction by gully-landslide interactions. One new gully found in Obibi-Ochasi had severed the road linking Asaa & Obibi-Ochasi communities (figure 7.1). Focus group respondents traced the source of the gully to a “minor fault” in the drainage channel constructed next to the road. They said they had notified the road contractors of the fault in the drainage channel but got no response. “Subsequently, concentrated runoff flowing in the drainage channel spilt on to the surrounding lands and initiated the gully” they concluded. Since this connecting road in Obibi-Ochasi was destroyed, commuters resorted to using nearby farmlands as footpaths and roads for motorcyclists, as observed during the field visit.

Figure 7.1: Destroyed connecting road linking Asaa & Obibi-Ochasi communities.

Secondly, loss of habitat was identified. An interview with a community member in Urualla revealed the loss of one their community streams to deposits from gully erosion. He recalled that as a child in the middle of 1970s, he and his peers would go down to the then small depression (now Urualla_gully1, Table 5.5) and cross it on their way to the stream. There were two streams, *Agwura Ukwu* and *Agwura Nta*, in the community at the time. According to the interviewee, between 1975/76, *Agwura Ukwu* "dried up". Today, *Agwura Nta* is also "endangered due to siltation from the gully". He continued "the villagers did not understand why their stream dried up; it is only becoming clear to them now that siltation from gully deposits could have been a potent reason for the drying up of *Agwura Ukwu".* He concluded "the sacred fish in the streams were not fished, but as the river dried up, the fish died". Based on this interview, there has been loss of habitat due to the complete disappearance of the *Agwura Ukwu* stream.

Thirdly, loss of houses and forced relocation. Respondents provided answers on forced relocation (Table 7.8), loss of houses/property to gullying (Table 7.9) and identified how they have been affected by gullying (Table 7.10). In Amucha, 55 respondents agreed they have been forced to relocate because of gully erosion (Table 7.8) while 43 respondents suggested that between 1 and 10 houses/property have been lost to gullying in their community in the last 10 years (2009 – 2018) (Table 7.9). A total of 45 people in Amucha community chose “C”, 44 selected “E”, 35 respondents ticked “A” while 30 respondents identified “D” as gully effects on them respectively. In Obibi-Ochasi, 60 respondents ticked “E” and 36 identified option “A” as gully effects on them (Table 7.10).

Table 7.8: Responses to question 9: In the last 10 years, have you been forced to relocate because of gully erosion? A) Yes, I have relocated due to gully erosion B) I would have relocated if I had a safe place to go to C) No, I have not relocated due to gully erosion D) No, but if the gullies continue expanding, I will have to relocate.

		Amucha					Obibi-Ochasi					
Age (years)	**Sex**						**Sex**					
	Male respondents	A	B	C	D	Total	Male respondents	A	B	C	D	Total
18-28	6	5			1	6	15		4	10	2	16
29-39	13	2	3	6	2	13	5			1	4	5
40-49	18	10	4	2	2	18	9	2	4		6	12
50-59	8	7	1			8	8	2	1		5	8
≥ 60	7	4	2		1	7	5		2		3	5
Total	52	28	10	8	6	52	42	4	11	11	20	46
	Female respondents						Female respondents					
18-28	8	9				9	12		5	7	1	13
29-39	8	2	2	2	1	7	4	1	1		3	5
40-49	15	11	3		2	16	7	1	2		5	8
50-59	6	2	4			6	2				2	2
≥ 60	3	3				3	1	1				1
Total	40	27	9	2	3	41	26	3	8	7	11	29

Table 7.9: Responses to question 11: How many houses/property have been lost in this autonomous community to gully erosion in the last 10 years? A) I am not aware of any B) 1 – 10 C) 10 – 11 D) 11 – 20 E) > 20.

		Amucha						Obibi-Ochasi				
Age (years)	**Sex**							**Sex**				
	Male respondents	A	B	C	D	E	Total	Male respondents	A	B	E	Total
18-28	6	1	5				6	15			15	15
29-39	13	5	5	1	2		13	5			5	5
40-49	18	1	6	3	3	4	17	9	1		8	9
50-59	8		2	2	2	2	8	8			8	8
≥ 60	7			3	3	1	7	5			5	5
Total	52	7	18	9	10	7	51	42	1	0	41	42
	Female respondents							Female respondents				
18-28	8		7		1	1	9	12			12	12
29-39	8	3	2	3			8	4		1	4	5
40-49	15		12	3		1	16	7		1	7	8
50-59	6		3	2	2		7	2			2	2
≥ 60	3		1	1	1		3	1			1	1
Total	40	3	25	9	4	2	43	26	0	2	26	28

Table 7.10: Responses to question 12: How does gully erosion affect you? A) Inaccessibility to farm B) Severance of communication links C) Collapse of houses D) Threat to my property E)Reduction in farmland F) Death of a loved one G) Others.

		Amucha								Obibi-Ochasi					
Age (years)	**Sex**														
	Male respondents	A	B	C	D	E	F	Total	Male respondents	A	B	C	D	E	Total
18-28	6	3		2	4	3	1	13	15	4				14	18
29-39	13	2	4	8		1		15	5	4				5	9
40-49	18	7	2	11	9	6		35	9	4			2	8	14
50-59	8	2		3	1	4		10	8	6			1	7	14
≥ 60	7	4		1	1	3		9	5	4				3	7
Total	52	18	6	25	15	17	1	82	42	22	0	0	3	37	62
	Female respondents								Female respondents						
18-28	8	3	1	3	1	13	2	23	12	2				11	13
29-39	8		1	4	1	2		8	4	5				4	9
40-49	15	10		10	11	9		40	7	5	1	1	1	5	13
50-59	6	3	1	2		2		8	2	1				2	3
≥ 60	3	1		1	2	1		5	1	1				1	2
Total	40	17	3	20	15	27	2	84	26	14	1	1	1	23	40

Participants at focus group meetings were asked to tell me how they have been affected by gully erosion. In Obibi-Ochasi, one of the community elders said “my house is next in line to be destroyed by the gully erosion and I have exhausted all avenues since 1981 to get the issue of gully erosion solved but to no avail hence, I have now resorted to prayers”. He went further “God has stopped the gully from growing for the last 4 years”. During fieldwork, it was observed that this gully is heavily vegetated, and could be a potential reason for reduced gully expansion, as suggested by the meeting participant. In the words of other participants “our lands and farms are gone, our Okpii Stream is no longer accessible and there is severance of roads”. They concluded by stating that “all money coming from community levies go into erosion-control”. In Amucha, focus group participants identified inaccessibility to farms as a significant effect of gully erosion. Other effects of gullying mentioned during Amucha group meeting include hindrance to new developmental projects such as building new houses, need to buy lands to build houses due to destruction of ancestral lands, permanent forced migration out of the community into surrounding communities (victims could be referred to as “environmental refugees”), loss of building materials, forced internal displacement within the community and loss of agricultural yield.

Fourthly, abandonment of farmlands/reduction in food production. Respondents were asked if they have abandoned a piece of farmland due to gully erosion in question 10. Commercial farming was not observed in the communities visited; hence, household farms are of interest in this research. Farm-produce from these household farms are consumed by farm owners or sold at the community markets. 52 respondents from Amucha agreed they had abandoned a piece of farm due to gullying while 29 people identified they would have abandoned their farms if they had another place to cultivate the land (Table 7.11). During fieldwork, some farmlands where found less than 1 m from gully edges in Amucha, while some farmers cultivated the soil inside the gully complex itself. These observations suggest that maybe these farmers have nowhere else to farm, hence, they take the risk of farming so close to the gully edges. In Obibi-Ochasi, 41 respondents identified they had abandoned their farms due to gullying.

Finally, death has resulted due to gullying. Focus group discussants noted that three deaths were recorded when commuters drove straight into one of the gullies in Obibi-Ochasi without knowing the road had been damaged. This condition made the road contractors to block the road (figure 7.2) to prevent further occurrences.

Table 7.11: Responses to question 10: In the last 10 years, have you abandoned a piece of farmland due to gully erosion? A) Yes, I left my farm due to gully erosion B) I would have abandoned my farm if I had another C) No, I have not abandoned my farm due to gully erosion D) No, but if the gullies continue expanding, I will have to abandon my farm.

		Amucha					Obibi-Ochasi					
Age (years)	**Sex**											
	Male respondents	A	B	C	D	Total	Male respondents	A	B	C	D	Total
18-28	6	5			1	6	15	11	2	1	2	16
29-39	13	4	5	3	1	13	5	1			4	5
40-49	18	11	5		2	18	9	6	1		4	11
50-59	8	4	4			8	8	3	1		4	8
≥ 60	7	4	3			7	5	3			2	5
Total	52	28	17	3	4	52	42	24	4	1	16	45
	Female respondents						female respondents					
18-28	8	8				8	12	8	4			12
29-39	8	1	5	1	1	8	4	2			3	5
40-49	15	10	4		2	16	7	4			4	8
50-59	6	4	2			6	2	2				2
≥ 60	3	1	1		1	3	1	1				1
Total	40	24	12	1	4	41	26	17	4		7	28

Figure 7.2: Barricades aimed at halting further movement of commuters along the road.

Effects of gully-landslide interactions can be grouped into two: direct and indirect effects. Direct effects include reduction of farmland, inaccessibility to farmland, loss of land and property, severance of communication lines, loss of habitat, economic losses and death. Indirect effects include effects on the environment, time wastage, increase in price of available food products, hunger and malnutrition and loss of seedling for next growing season.

Results presented in this section indicate that both focus group participants and questionnaire respondents recognised direct effects of gully erosion on food production. These effects could be in the form of inaccessibility to farmlands, reduction in farmland (Table 7.10) or through desiccation of crops close to the gully edges (Frankl et al, 2016). Inaccessibility to farmlands has the following implications: First, inability to cultivate the land. When the land is not cultivated, not only is there pressure on cultivated lands, but there is also reduction in available food production. Secondly, when there is reduction in available yields, there is the possibility all produced food crops would be consumed which means there may not be sufficient crops for planting in the next growing season. Furthermore, insufficient seedlings, an indirect effect of gullying means fewer crops will be planted which then means less food would be produced and this cycle could lead to a continuous chain of events where there is lesser food available every year despite increase in population and population density. Increase in population density further emphasises why some farmers are cultivating lands on marginally stable lands despite risks to their safety and possible reduction in yield due to desiccation. Moreover, inaccessibility to farmlands will lead to decomposition of un-harvested farm-produce which translates into reduction in available food and lower food products to be sold in the market as well as economic loses. The available food products in the market will likely be sold at higher prices (an indirect effect of gullying) which will reduce purchasing power of some people. Reduced purchasing power will possibly lead to hunger and malnutrition among some segments of the society.

When communication lines such as roads are destroyed, commuters seek alternative routes to get to their destinations. In some cases, these alternative routes involve longer distances which translate into time wastage and prolonged emission of carbon dioxide (thus increasing supply of greenhouse gases) and various chemicals and pollutants into the atmosphere. In other cases, when roads are destroyed, nearby farmlands can be used as alternatives. This situation was observed in Obibi-Ochasi. Converting a farmland into a road for both pedestrians and motorcyclists has some implications; it can increase compaction of soils in the farms (Bakker and Davis, 1995) and thereby reducing infiltration and increasing surface runoff (Posthumus et al. 2011). Judging from the proximity of the converted farmlands in Obibi-Ochasi to the gully edges, higher runoff volumes will flow into the gullies and thereby further destabilizing the gully wall and possibly facilitate gully expansion into the farmland. Furthermore, compacted soils may hinder appropriate root development of crops, impede crop development, reduce crop yield and therefore render the soils unsuitable for agricultural production (Posthumus et al. 2011; Rickson et al. 2015). Soil erosion and soil compaction are examples of land degradation (Rickson et al. 2015) but in the study area, soil compaction can be a product of soil erosion which creates favourable conditions (increased surface runoff) for gully expansion. This positive feedback between gullying and soil compaction can further enhance the effects of land degradation. Continuous use of farms for commuting will reduce available farming space which may lead to reduction in farmers' yield and possible income. Additionally, when pedestrians and cyclists use the same tiny footpaths (observed in Obibi-Ochasi), there could be a higher risk of accidents. This factor is made worse by reduced visibility due to crops planted in the farm. Finally, commuters can accidentally damage planted crops thereby reducing farmers' yield and income. Therefore, there are implications for food production and security, as well as for safety of commuters due to the conversion of farms into "make-shift roads" due by gully-landslide interactions.

As gullies expand, neighbouring farmlands are lost, hence, farmers are forced to farm closer to the edges of the gully, as observed in Amucha and Isu Njaba, where yam and cassava farms were less than 1 m from the edge of the gully. Cultivated soil was also found inside the gully complex in Amucha. These farming activities have implications for safety, food production and gully expansion. For example, gully depths in Amucha and Isu Njaba are up to 35 m in places, an accidental fall into the gully during farming will cause harm to a victim. Desiccation of crops close to gully edges is known and documented (Frankl et al. 2016), hence, it is possible, cultivated crops will have poor yields which could negatively affect the economic power of the farmer, as well as food security of the community. Constant farming close to the gully edge might channel surface runoff into the gully, especially, where farmers cultivate the land along slope and not across slope (Panagos et al. 2015; Chalise 2019). A case in point was observed in Isu Njaba where cassava was planted in mounds made along the slope, thereby making pathways for surface runoff to flow directly from the farm into the gully. Further, cultivating the soil inside the gully complex may discourage natural vegetation colonization which could enhance gully stabilization. Since bush burning is a common agricultural practise, farm clearing at the outset of rainy season would leave the gully bare and may increase susceptibility to gully expansion due to increased volume of surface runoff.

With reference to loss of houses, the questionnaire survey (Table 7.9) and focus group discussion results from both Amucha and Obibi-Ochasi showed that gully-landslide interactions pose a threat to property and houses. During fieldwork, I observed parts of destroyed houses which have been deposited within the Amucha gully. Some people have been forced to become "environmental refugees" in their ancestral homes as identified during focus group meetings. One of the women we met during fieldwork to Obibi-Ochasi said to us "please tell them to come and help us as my house will soon be destroyed and I have nowhere to go". In the study area, the ancestral home holds a special place in the lives of citizens, and loss of ancestral homes and means of livelihood due to gullying could affect victims economically, socially and psychologically.

7.3 Control measures of gully-landslide interactions

Section C of the questionnaire focused on control measures adopted in the face of gully-landslide interactions. Results on section 7.3 are presented in the following themes: Firstly, individual and community efforts. Respondents were asked which soil-conservation techniques they employ to reduce gully-landslide interactions. A total of 66 respondents in Amucha wrote down tree-planting as a measure they adopt to reduce gullying (Table 7.12). In Obibi-Ochasi, 16 respondents identified tree-planting while five people recognised pits and flood diversion as soil-conservation methods they adopt. Focus group discussants in Amucha identified tree-planting around the gully edges as a gully control, popular plants are bamboo (Bambusoideae) and cashew (*Anacardium occidentale*). In Obibi-Ochasi, focus group participants observed that as a community effort, they dug pits in different parts of the community to retain surface runoff. Digging of pits as a gully control measure began in 1991. These pits which measured 3 m deep and 6.7 m wide are cleaned yearly by community effort just before the outset of heavy rainfall. There were mounds around the pits which were designed to hold water from spilling out. Focus group discussants informed me there are about 25 of such pits dug at various points in the community. Drainage channels are dug and channelled into these pits. According to focus group participants, earth pits are effective in reducing gully expansion.

Interviews with respondents revealed that sand mining has been banned in Amucha and Umueshi communities while focus group participants in Obibi-Ochasi said they have asked the communities downstream to stop mining sand, but this request was not respected. In their words, “The speed of sand excavation is same speed of erosion in our community”. A yet-to-be implemented gully-control technique suggested during group meeting in Obibi-Ochasi was the use of retention pits in every compound. In their words, “if the use of retention pits for every compound is implemented in our community, it could reduce gullying”. Meeting participants acknowledged the use of retention pits in the neighbouring State.

Table 7.12: Responses to question 21: Which other soil-conservation methods do you employ?

		Amucha			Obib-Ochasi		
Age (years)	**Sex**				**Sex**		
	Male respondents	tree planting			Male respondents	tree planting	pits for flood diversion
18-28	6	5			15	8	
29-39	13	5			5	1	1
40-49	18	11			9		
50-59	8	7			8		

≥ 60	7	6			5		3
Total	52	34			42	9	4
	Female respondents				Female respondents		
18-28	8	4			12	7	
29-39	8	7			4		
40-49	15	14	contour terrace	Sand-filling	7		
50-59	6	4		Sand-bags	2		1
≥ 60	3	3			1		
Total	40	32			26	7	1

Respondents were asked if they insured their houses and property against gullying. 68 respondents in Amucha remarked they would like insurance but cannot afford it while 44 people noted they do not have insurance cover for their houses. In Obibi-Ochasi, 65 respondents noted they do not have insurance cover for their homes. I spoke with two insurance companies operating in the state about offering insurance against gullying, and both were not sure what I meant by insurance against gullying. One of the companies said their policies covered flooding, lightning, and thunderstorms, but with reference to gullying, they said “no insurance policy was in place and this is because the area is endemic to gullying”. They continued “however, a special arrangement could be made to insure the house, this will be more expensive than the usual insurance cover available for flooding or lightning and will involve visit by experts to ascertain proximity of the said buildings to an existing gully”.

The second control measure identified was in the form of external aid. External aid was received from the government, Non-Government Organizations (NGOs) and International Non-Government Organizations (INGOs). Focus group meetings and interview with respondents in Amucha identified previous interventions of the Local Empowerment and Environment Management Projects (LEEMP), a World Bank-assisted project, as an external intervention. I was informed that LEEMP constructed drainage channels to control surface runoff, with the aim of reducing gully expansions. A local NGO, The Amucha Ohonya Erosion and Ecosystem Foundation, was formed with the aim of monitoring, raising awareness and soliciting for aids for the controls of the Amucha gully. This NGO has volunteers who guide visitors and researchers visiting the Amucha Gully complex. The NGO is also involved in tree-planting around the gully edges with the aim of stabilising the gully. In Amucha, the Federal Government constructed drainage channels between 1983/84 to direct surface runoff into the Njaba River as a gully-control measure. Focus group respondents believed this drainage channel helped deter gully expansion momentarily, however, some parts of this channel were under threat of collapse during fieldwork (figure 7.3). This condition has the people worried about the future of the drainage channel in controlling surface runoff and by extension, erosion. In Obibi-Ochasi, the Niger Delta Development Commission (NDDC), the Nigeria Erosion and Watershed Management Project (NEWMAP) and the World Bank were external bodies who had been involved in gully-control in the past, according to focus group meeting attendees. Focus group participants in Obibi-Ochasi informed me that 362 seeds of gmelina (*Gmelina arborea*) were planted in the 1980s around the gully edges by the government and the community believes these trees reduced the speed of gully growth. During an interview with the chairman of the gully-control committee in Obibi-Ochasi, he showed me seven letters which the community had written (between 1994 and 2011) to successive governments asking for assistance to control gullying but he received no response. Focus group and interview participants in both communities believe gully-control measures adopted so far though not in vain have not been sufficient to stop gully expansion.

During fieldwork, it was observed that the Nigeria Erosion and Watershed Management Project (NEWMAP), a World Bank-assisted project aimed at controlling gully erosion in gully-prone states, was carrying out gully-control measures in Urualla community. Participants at focus group meetings in Amucha said “NEWMAP would not intervene in the Amucha gully due to the vegetated nature of the gully”. They went further to say that NEWMAP informed them that “the vegetal cover around the gully shows the gully is stabilizing and therefore no intervention was required”. In Obibi-Ochasi, focus group meeting participants said that NEWMAP had visited the community and conducted feasibility studies “but nothing else was heard from them”. In Umueshi, NEWMAP started gully control works but the project was abandoned mid-way. In Urualla, gully rehabilitation works were observed during fieldwork. Increase in gully sizes were identified in Amucha, Umueshi and Urualla communities.

Figure 7.3: Drainage channel constructed by the Federal Government in Amucha in 1983/84 as a gully-control. Some parts of the structure are under threat of collapse as shown in this image and this condition has residents of the community worried.

This section has enumerated individual and community efforts aimed at reducing gully expansion. One central theme that emerged from interviews, focus group meetings, questionnaire survey and field observation is the use of tree-planting around the gully, as a gully-control measure. Two types of plant species are often planted, the bamboo and cashew. These species have the following features which may have been deemed sufficient for gully stabilization:

1. Bamboo can grow rapidly (they are among the fastest growing plants) and colonise a territory (Ben-Zhi et al, 2005) hence they may have been considered adequate to reduce surface runoff and increase infiltration.

2. Bamboo has a fibrous root system (0 – 30 cm) of tightly woven mat and rhizomes which are thought to hold soil particles together at the surface.
3. Bamboo is a cash crop that is harvested and used for several activities from supporting yam sampling to building construction (figure 7.4). Bamboo produces new culms from underground rhizomes which allows harvesting without disturbing the soil (Ben-Zhi et al, 2005).
4. Bamboo grows well on steep hillslopes (Ben-Zhi et al, 2005).
5. Cashew trees are fast growing, tropical and can live up to 50 years.
6. Cashews have long fibrous roots (growing laterally up to 7 m) and deep tap root (up to 5 m) (Tsakiris & Northwood, 1967; Dendena & Corsi, 2014).
7. Cashew is a cash crop and hence, the communities will protect the plant, while they help to stabilise the soils.

Regarding farming techniques, farmers in Amucha made mounds of cassava across slope to reduce volume and speed of surface runoff (figure 7.5). This farming technique is a learned behaviour which these farmers have adopted. In contrast, cassava mounds in Isu Njaba were cultivated along the direction of the slope, such that the grooves between mounds could serve as a channel for surface runoff to flow into the gully. Both farms were adjacent to gully walls. In Umueshi community, the NEWMAP had paid farmers whose farms were adjoining the gully so they would not till the soil and allow gully rehabilitation projects to proceed unhindered. If farmers in other gully-prone communities whose farms were bordering gullies were paid so they would not till the soils and allow natural vegetation to colonise such lands, then effect of surface runoff as a gully driver around these lands might be reduced. However, vegetal colonization could increase susceptibility of gully walls to erosional activities by sub-surface flow.

A community effort aimed at retaining surface flow which was observed only in Obibi-Ochasi was the digging and cleaning of pits. If other communities affected by gullying adopted this technique, volume of runoff flowing into gullies would be reduced. These pits could pose few challenges, for example, drainage channels are dug to direct surface flow into them. These drainage channels which are not cemented could be widened due to erosion by surface runoff, and thereby leading to expansion and possible gully initiation. Secondly, digging of pits while serving as a gully-control measure leads to loss of land for farming or other activities. Lands used for retention pits may not be suitable for any other activities in the future, and hence, could be a reason use of this community technique is not popular in other communities.

Figure 7.4: Bamboo sticks used for building construction. One of the numerous uses of the bamboo which is a cash-crop.

Figure 7.5: Freshly cultivated cassava farm adjacent to the Amucha gully. Mounds are made across slope to encourage infiltration and reduce volume of surface runoff flowing out of the farm.

Community efforts to reduce gullying adopted in other communities include a ban on sand mining. For example, in Umueshi, sand mining was banned in 2017. Face to face interview with local guides in Amucha revealed that the community is losing revenue due to their inability to mine earth materials in the gully. For instance, despite the abundance of marine sandstone (white sand) and chalk within some sections of the gully, these resources are not mined for two reasons; inaccessibility due to gullying and secondly, so as not to expedite landsliding and gully expansion. While the ban on sand mining could be regarded as a control measure aimed at reducing gully expansion, it also means sand vendors have to relocate to other communities to trade and thus, there is loss of employment opportunities and income. Further, the cost of transporting these materials (chalk and marine sandstone) from neighbouring communities to Amucha may be more expensive than if they were able to mine from their community.

Regarding external aid, results from this section show that since the 1980s, the study area has attracted the attention of external support to curtail gully expansion. However, it is the belief of interviewees and respondents that the aid they have received are not sufficient. While some visited gullies were vegetated, they showed signs of activity, for example, fresh landslide scars (Amucha gully) or spring discharge (Obibi-Ochasi gully). These conditions suggest that the use of surface runoff-control measures as attested to by respondents as a gully-control may not be the only solution to curtail gully-expansion in the study area. The idea that presence of vegetal cover around or within sections of a gully mean the gully is stabilizing (as suggested by the interaction between the community and NEWMAP) may not be true in all cases as vegetation cover can increase susceptibility to landsliding (Greenway, 1987). Therefore, different actions are needed to stop existing gullies from expanding compared to measures to stop new gullies from forming. For example, while control of surface runoff may deter development of new gullies, it may not prevent old gullies from expanding.

7.4 Summary

In this chapter, results of hazards and effects of gully-landslide interactions have been presented and discussed. Respondents identified effects of gullying on their farms and houses as the key problems they face (section 7.2). These responses are reasonable as it is easier to relate with the present than it is with the future. Food and shelter are important needs of humans; however, gully-landslide interactions can rob people of their abilities to provide both needs. Some indirect effects of gullying were also identified in this chapter such as higher release of carbon dioxide due to longer distances required to travel. This effect could add to greenhouse gases and further exacerbate the problem of climate change. Community and individual efforts have been adopted to reduce effects of gullying; these efforts according respondents have been effective in slowing the pace of gully expansion in the last 10 years. Despite initial successes recorded in combating gully erosion, affected communities feel more external aid is required to slow gully expansion.

7.5 Conclusions

The following are the conclusions of this chapter:

1. Regardless of age, there is a high level of awareness among inhabitants of the study area on the hazards of gully-landslide interactions. Despite cultural similarities, indigenous knowledge regarding causes of gully erosion slightly differs between the two communities where focus group meetings were conducted.
2. Results shown above indicate that the effects of gully-landslide interactions can be direct (e.g. reduction in arable lands) or indirect (higher prices of available food products). While it is easier to relate with direct effects (as identified from questionnaire, interview and focus group meetings), indirect consequences of gullying identified in this study can be profound.
3. There are community and individual efforts involved in reducing impacts of gully-landslide interactions. Tree planting is a well-known gully-control technique and has been adopted for a long time, however, this technique has not been effective in deterring gully growth.
4. Since the 1980s, there have been external aids to combat gullying in the study area although not in vain, these efforts have not stopped old gullies from expanding or the formation of new ones.

Chapter 8

Discussion

This chapter is a synthesis of the result chapters (4 – 7). Discussions centre on the conceptual model (presented in section 2.3) which formed the foundation for posing research questions in this study. Section 8.1 presents an evaluation of the old conceptual model centred on literature review only, while section 8.2 discusses a modified conceptual model based on the results presented in chapters 4 – 7 and literature review. This modified model is informed by the findings of this research. Gully-management recommendations are discussed in section 8.3 while summary and conclusions follow in section 8.4.

8.1 Evaluation of old conceptual model of gully landslide interaction

The conceptual model developed in section 2.3 identified the relationships among climate, geology, soil, geomorphology and human activities which influence gully-landslide interactions, (figure 2.4). In chapter 4, the influence of land use and land-use changes as gully-drivers were identified. While section 2.3 acknowledged human activities including removal of vegetation as gully drivers, the likely role played by civil war (increased demographic pressure, digging bunkers) as a gully-driver was not captured. Combined actions of land-use changes, relative relief and nearness to rivers and roads influence changes in gully sizes in the study area (section 4.5.1) but was not identified in section 2.3. Removal of vegetal cover and increase in non-vegetated surfaces are known to enhance gullying (Ionita et al. 2015) as shown in figure 2.4, however, section 4.3 suggests that gullies in different catchments react differently to similar land-use changes. This result points to the uniqueness of individual catchments and gully responses to other drivers of gully expansion other than land-use changes – a factor not recognized in section 2.3.

It is known that surface runoff is the primary driver of gully erosion, especially, at the early stages of a gully (Okagbue & Uma, 1987; Betts et al. 2003; Poesen et al. 2003; Frankl et al. 2021) as identified in section 2.3. However, modelling results in section 5.1.2 suggest that in addition to surface runoff, sub-surface flow-driven erosion is a potential process of gullying in the study area. Fieldwork revealed the presence of springs and landslide scars in some visited gullies, some of which were vegetated (e.g. Amucha gully) while modelling results indicated high volumes of lateral flow in some gully-adjacent sub-basins (figure 5.17). Focus group meeting attendees informed me that landsliding only occurred a day or two after rainfall (section 7.11), suggestive of the potential effect of groundwater as a landslide-driver. Whilst section 2.3 identified porewater pressure as a trigger of landsliding, sub-surface flow as an erosional agent did not receive adequate attention in the conceptual model. Thus, there are important mechanisms not included in the conceptual model (figure 2.4) that are clearly essential to produce a more complete conceptual model of gully-landslide interactions.

8.2 Modified conceptual model of gully-landslide interactions

8.2.1 Human-vegetation interactions

Figure 2.4 identified that land-use changes, especially the removal of vegetal cover, will facilitate susceptibility of soils to gully erosion. Across the entire study area, land use changes were recorded for the study period, non-vegetated surfaces occupied 58.6 km^2 in 2009 but increased to 144.7 km^2 in 2018, an increase by 146.8%, conversely, there was a reduction in tree/fallowed lands from 281.2 km^2 in 2009 to 57.8 km^2 in 2018, a reduction of 79.5% (section 4.1). During same study period, gully numbers rose from 26 in 2009 to 39 in 2018 while gullied area grew from 0.36 km^2 to 0.62 km^2 thus, there was an increase of 50% and 75% in gully numbers and gullied areas respectively (section 4.2). These results are consistent with the observations of Ionita et al. (2015) and Castillo et al. (2016) who suggested that gully evolution is linked to major land-use changes, especially, reduction in forested lands. An example of land-use change is road construction which often involves conversion of land from vegetated to paved surfaces. Results from the study area regarding gully evolution and nearness to roads (section 4.4) are similar to those reported in other parts of the world, e.g. southern Spain (Collison, 2001), northern Ethiopia (Frankl et al. 2012), southeast Nigeria (Nwankwor et al. 2015), the Ilam, Lorestan and Mazandaran Provinces of Iran (Rahmati et al. 2017; Zabihi et al. 2018).

Vegetation communities affect soil erosion through their impact upon hydrology and soil structure (Wainwright & Parsons, 2010). In this study, effects of vegetation on soil structure were not studied, however, results in section 5.1 suggest that reductions in tree/fallow cover results in higher flow of surface runoff and surface runoff is recognised as a primary driver of gully erosion (Poesen et al. 2003). Across some catchments (e.g. Amucha, Orlu1, IdeatoSouth2, IdeatoNorth1), higher surface runoff estimates due to changes in land use corresponded with increase in gully dimensions (section 5.3). Hence one can cautiously say that factors that increase surface runoff (e.g. increase in non-vegetated surfaces) will potentially increase gully sizes and numbers. Research findings presented in sections 4.1, 4.2, 4.4 and 5.3 support the section of figure 2.4 that proposes higher susceptibility of soils to gully erosion due to conversion of lands from vegetated to non-vegetated surfaces (figure 8.1).

Apart from removal of vegetation and increase in non-vegetated surfaces, another factor of human origin that was identified through focus group meetings as a gully-driver is civil war. Figure 2.4 does not capture civil war as a factor of interest in gully-landslide interactions. Bomb explosion is a process of soil erosion in the Anthropocene (Poesen, 2018). Focus group discussions (section 4.4.2) detail changes to the pristine nature of the environment during the civil war, these changes including sudden increase in population density and military activities of the defunct Biafran soldiers, were said to have led to the initiations of the oldest gullies in the study area (1968 in Obibi-Ochasi and 1969 in Amucha). Although increase in demographic pressure has been suggested as a gully driver (Fanciullacci, 1978) and is captured in figure 2.4, the role of civil war first as a catalyst of increased demographic pressure and secondly, as a driver of gully erosion in the study area has not been documented and is included in the modified conceptual model (figure 8.1).

8.2.2 Sub-surface-driven gullying

Sub-surface erosion which can occur through seepage erosion (Dunne, 1990), actions of lateral movement of water within the soil (Berry, 1970), groundwater driven erosion (Okagbue & Uma, 1987) as well as piping (Bernatek-Jakiel & Poesen, 2018). Modelling results showed that while some gully catchments witnessed increased non-vegetated surfaces and subsequent rise in surface flow, two catchments (IdSouthWS1 and Njaba WS1) experienced reductions in non-vegetated areas (Table 4.4). In IdSouthWS1 for example, a continuous increase in fallow/tree cover was noticed between 2009 and 2018. Whereas there could be changes in land use in one direction (e.g. reductions in fallow/tree cover) in parts of a catchment, land use changes in the opposite direction (e.g. increased fallow/tree cover) in other parts of same catchment were possible (e.g. in Njaba2 catchment, figure 5.18, there was reduced fallow cover across the catchment, yet sub-basin 20 saw higher fallow cover from 2009 to 2018). These variations in land use have implications for surface runoff or sub-surface flow as potential gully drivers.

Presented results from Njaba2 and IdSouthWS1 catchments (section 5.1.2) suggest that in addition to surface runoff, sub-surface flow is also a possible gully driver in the study area but was not included in figure 2.4. Higher lateral flow volumes were modelled for sub-basins with higher slope angles (section 5.4) and thus, while topography directly controls erosivity of surface runoff (Knapen & Poesen 2010), modelled results indicate topography also affects volume of lateral flow, which might likely influence erosivity of lateral flow, a view supported by Micallef et al. (2021).

Regarding landslides, higher pore pressure enhances susceptibility to slope failure (Akpan et al. 2015; Igwe. et al. 2016; Maduka et al. 2017) and thus, actions that increase infiltration or agents that create preferential pathways for waterflow such as plant roots (Wainwright, 2009) will likely increase pore pressure and subsequently reduce resistance to sliding. Further, increased weight of soil due to higher infiltration and weight of trees may potentially enhance sliding, and finally, transmission of kinetic energy from trees into gully slopes will lead to reduced shear strength of gully slopes and higher susceptibility to gully-induced landslides (Greenway, 1987). Different processes of landsliding which involve removal of earth materials in large volumes can be driven by groundwater and can bring about gully expansion (Okagbue & Uma, 1987). Landsliding may become active up to several days after a large rainfall event due to the time it takes for rainwater to reach the groundwater store (Betts et al. 2003). A focus group meeting at Obibi-Ochasi (section 7.11) revealed that sliding occurred not during rainfall, but a day or two after rainfall, thus pointing to the potential role of groundwater as an agent of gully-induced slides.

During site visits, fresh and old landslide scars were observed in visited gullies (e.g. Amucha, Obibi-Ochasi and Isu Njaba) despite the vegetated nature of the lands surrounding the top of the gully. It is possible higher infiltration due to the vegetal cover of gully tops, or increased weight of slope materials or transmission of kinetic energy from tree canopies into the hillslopes, or removal of toe support due to surface runoff flowing through the gully floor, or combinations of all four factors are responsible for slope failures within these gullies. Figure 2.4 illustrates that transmission of kinetic energy from vegetal cover can increase susceptibility to landsliding and field observation indicates gullies in the study area whose tops were vegetated experience slope failures. Favourable conditions such as irregular and bare surfaces created by gully-induced landslide scars will increase propensity to gully widening (Johnson & Warburton, 2015; Gómez-Gutiérrez et al. 2015).

8.2.3 Climatic influence on gully-landslide interactions

Increase in temperature increases evapotranspiration losses as identified from modelling results across catchments covered in the 2014 satellite data (e.g. IdNorthWS, figure 5.10). This situation can decrease or increase susceptibilities to gully erosion and landsliding. Reduction in susceptibilities to both processes' manifests in the loss of sub-surface flow through transpiration from plants, and thus, less lateral and groundwater flows are available to destabilise gully slopes (Greenway, 1987). The adverse effect of rapid evaporation due to higher temperature relates to condensation of evaporated water. In favourable conditions (e.g.

availability of condensation nuclei) water vapour could condense and return to the surface as rainfall (Entekhabi et al. 1992), and hence, rapid evapotranspiration can facilitate higher condensation which may in turn lead to more convectional rainfall. These convectional rains when armed with sufficient kinetic energy can erode soils especially, when they fall on bare surfaces caused by removal of vegetal cover by either human activities or landslide scars.

Climatic elements interact with other gully-drivers, e.g. land-use changes, to influence gully-landslide linkages. For example, modelling results show that 2009 was the wettest year, yet streamflow in some catchments were higher in either 2014 or 2018 (e.g. IdNorthWS, figure 5.10) due to land-use configurations. Based on modelled results, in areas of higher vegetal cover, the following happens to rainfall:

1. Higher infiltration occurs.
2. Depending on local slope configuration, infiltrated water either percolates and joins groundwater contribution to streamflow or flows laterally.
3. Areas with higher slope angles have higher lateral flow contribution to streamflow.
4. Catchments with lower slope angles have higher percolation, higher groundwater flow contribution to streamflow and higher loss to deep aquifer.

If the land use is dominated by connected non-vegetated surfaces:

1. Less infiltration occurs.
2. There is higher surface runoff contribution to streamflow.
3. There is less percolation and lesser loss of water to deep aquifer.
4. In summary, there is higher streamflow even though total rainfall could be smaller (e.g. IdNorthWS, figure 5.10).

8.2.4 Geomorphic drivers of gully-landslide interactions

In section 4.4.1, results on relative relief, maximum slope and curvature were presented. Principal Component Analysis indicated that along the first principal component, both relative relief and maximum slope had same effect (Table 4.7), also, multiple regression results indicate that relative relief alongside nearness to roads and rivers correlate with changes in gullied area (P-value = 0.03, $r^2 = 0.3$, adjusted $r^2 = 0.21$, Table 4.9). With respect to curvature (curvature as a geomorphic variable was not included in figure 2.4), higher concentration of gullies was identified on convex curvature (Table 4.12) and suggests there are higher gully counts on the portions of the slopes where flow acceleration is observed in contrast to where flow accumulation dominates. Section 4.4.1 shows there is higher gully concentration around rivers while a sharp rise in slope from 0 – 58.2% within a distance less than 500 m from the river was observed. Therefore, accelerated surface flow draining into the rivers likely increase gully sizes and gully concentration around rivers. Also, deposited materials which ordinary should protect gully-foots from further erosion are carried away by ephemeral flows and deposited in the rivers (observed in the field) due to nearness of gully endpoints to rivers (figure 4.18). This situation creates a positive feedback mechanism such that as more materials are carried away by rivers, more deposits are eroded from gullies.

There is reduction in factor of safety with increasing slope angle (Figure 6.3). Landsliding is of relatively minor importance in the early stages of gully development (except where gullies are triggered as a result of landsliding) when surface erosion and fluvial incision dominate but becomes increasingly important as gully development passes a critical threshold of sidewall length and/or slope, and sidewalls then begin to fail (Betts et al. 2003). This observation is supported by Okagbue & Uma, (1987) who proposed four stages of gully evolution. During the first three stages, surficial removal of soil particles by rainfall and surface runoff along rills and gullies are the main erosional activities while landsliding is dominant at the final phase (Okagbue & Uma, 1987). In figure 2.4, I proposed that higher slope angles caused by gully erosion facilitate landsliding, and section 6.12 details three processes of gully-induced landsliding observed in the field, which lead to gully expansion. Figure 6.9 shows bare and rough surfaces (formed from gully-induced slides) which present favourable conditions for gully sidewall erosion, a process of gully widening (Wishart & Warburton, 2001; Castillo & Gómez, 2016). Thus, field observations, regression analysis results and modelled factor of safety results support the section of figure 2.4 that associates slope angles with increased susceptibilities to gully erosion, gully-induced landsliding and in turn, landslide-induced gully expansion (figure 8.1).

8.2.5 Nearness to rivers

There is a positive association between gully head distance from rivers and change in gullied area (0.5) and change in gully length (0.41, figure 4.17). Zabihi et al (2018) also found higher gully concentration in lands closer to rivers. Combinations of factors enumerated in section 4.5.1 likely facilitate concentration of gullies in river-adjacent lands.

8.2.6 Soil attributes and gully-landslide interactions

In section 4.4.1, results on different soil attributes were presented. The soils in the study area have higher sand content and infiltration results (Tables 4.13 and 4.15). Higher sand content can lead to lesser resistance of soils to dispersal by rainwater, high infiltration rates (up to 3571 mm/hr) and in turn, increased seepage erosion (Obi & Asiegbu, 1980; Okagbue & Ezechi, 1988). Hence, there is tendency that sub-surface erosion will be dominant in vegetated areas, while in non-vegetated catchments, surface runoff erosion might be a significant gully-driver. There is the possibility of a continuum where both processes control gullying at different periods (section 5.3) or during different seasons of a year such that at the beginning of the rainy season, surface flow is a dominant gully-driver, while in the middle of rainy season, sub-surface flow dominates (section 5.4). As the gully walls attain steep slopes due to intense gullying, mass movement sets in thereby creating irregular surfaces conducive to enhance gully width expansion, and thus the cycle gully-landslide interaction continues. Infiltration rates of soils, soil texture and the derived effect of seepage pressure due to high sand content which are important in gully-landslide studies were not illustrated in figure 2.4. As a result of the above discussion and identification of gaps, I have developed a revised conceptual model of gully-landslide interactions (Figure 8.1).

While it has been stated previously in various chapters of this thesis that landslides can lead to gully formation, it is important to reaffirm here that the landslides studied in this project are gully induced. Based on evidence presented in chapter 6 (observed landslides were likely triggered by steep slope angles caused by gullying, or removal of slope toe support by erosion or combinations of both processes) it is clear that gully formation through other ecogeomorphic interactions precedes gully-induced landsliding which is a product of extreme gullying. Thus, slope failure would not have occurred if gully erosion did not take place initially.

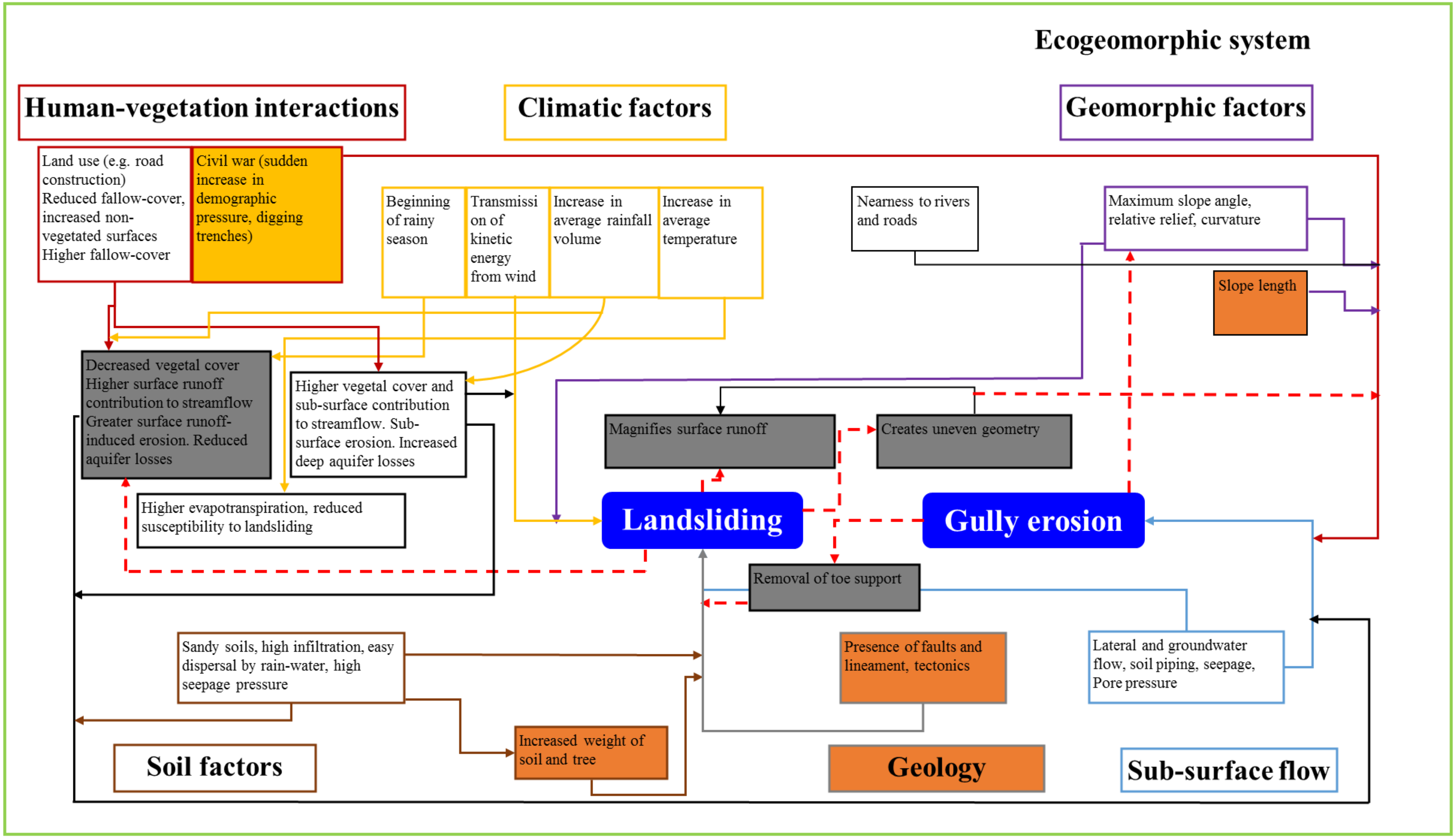

Figure 8.1: Modified conceptual model of the ecogeomorphology of gully-landslide interactions. Grey boxes and dashed lines show feedbacks between gully erosion and landsliding, green box indicates the ecogeomorphic system, orange boxes indicate factors not studied but derived from literature, gold box shows factors previously not studied in the region, white boxes were identified from literature and supported by research findings.

8.3 Management

Section 7.3 identified soil conservation and erosion-control measures adopted in the study area. In Amucha and Obibi-Ochasi communities, 66 and 16 respondents respectively, named tree planting as a method they adopt to reduce gullying. Popular gully-control plants are bamboo (Bambusoideae) and cashew (*Anacardium occidentale*), section 7.3 details likely reasons these plants are used for gully-control and soil conservation. Tree planting around gully edges (identified by focus group respondents), as an erosion-control technique may be inefficient if mass movement is the dominant driver of gully erosion (Betts et al. 2003; Valentin et al. 2005). Since 1935, different erosion-control methods including tree planting and engineering constructions designed to reduce erosive power of surface flow have been adopted to curtail gullying in southeast Nigeria (Egboka & Nwankwor, 1985). Tree planting and regulation of surface runoff are effective in controlling only shallow (< 15 m deep) gullies that have not cut through a saturated zone. These measures tend to fail when used for deep gullies that are greatly affected by groundwater especially when such gully floors are located in non-cohesive and very permeable sands (Okagbue & Uma, 1987). This observation by Okagbue & Uma (1987) is the possible reason some erosion-control projects have failed over the years.

Fieldwork identified gully rehabilitation projects undertaken by the Nigeria Erosion and Watershed Management Project (NEWMAP) at two visited gullies. While the project at the Umueshi community had been abandoned, work (in the form of gully reshaping which involes partial filling up and reshaping gully banks into stable slopes) was ongoing at the Urualla gully site. Interview with residents of Amucha community confirmed that NEWMAP officials had visited the Amucha gully but suggested there was no need for any intervention due to the vegetated nature of the gully. While it is possible that vegetation colonization on gully floor will reduce surface flow and gully-toe erosion by surface runoff, it has been suggested in section 8.2.3 that higher vegetal cover will likely increase infiltration which may enhance actions of sub-surface flow as gully-drivers. Higher vegetal cover on gully tops or walls can enhance higher sub-surface flow. Sub-surface flow leads to different types of gully-induced landslides which enlarge gully sizes (Okagbue & Uma, 1987). Transmission of kinetic energy from trees found on gully roofs or walls will enhance slope instability (Greenway, 1987). During fieldwork, multiple old and recent landslide scars where identified within the Amucha gully in spite of the vegetated condition of sections of the gully. Therefore, higher vegetal cover of the gully wall or roof does not necessarily translate into gully stabilization as was implied by the NEWMAP officials.

Modelling results and gully mapping have shown that while some gully sizes grew alongside increased surface runoff in their catchments, changes in gully sizes in other watersheds corresponded to increased sub-surface flow, and in some, gully changes in response to increased surface and sub-surface flows were observed. These results are important when designing gully-management methods. For example, controlling surface flow may work as a gully-control measure in a catchment whose gully responded to increased surface runoff, and where the gully depth is less than 15 m (Okagbue & Uma, 1987). However, the same gully-control method may be inefficient in a different catchment where gully changes are driven by sub-surface erosion. For gully management to be successful therefore, an understanding of ecogeomorphic interactions acting as gully-drivers within the gully watershed is vital. To this end, the following gully-management recommendations are offered based on findings of this research. These recommendations can broadly be divided into two phases: desk study and geomorphic delineation of gully catchment into sub-basins, and recommended management (figure 8.2).

1. Gully growth in response to surface runoff: by the time it has been established through initial desk study that gully growth corresponds to higher estimates of surface runoff over the years, the slope angles of individual sub-basins in the catchment should be identified. If the sub-basins are dominated by low-angle slopes, then lateral flow contribution to streamflow will be expected to be low while groundwater contribution to flow would be high (e.g. IdeatoSouth_gully2, Orlu1, Urualla_gully1). Hence, efforts should be geared towards controlling both surface runoff and groundwater flow into the gully. Concrete drainage channels aimed at carrying surface runoff (flowing from upstream sub-basins in a catchment) away from gullies and into local base levels such as rivers and retention dams will possibly reduce surface runoff erosion. Reducing groundwater flow into gullies from upstream and gully-adjacent sub-basins will possibly control groundwater-driven erosion.
2. If gully growth corresponds to higher surface runoff and sub-basins, especially gully-adjacent sub-basins are dominated by high slope angles, lateral flow contribution to streamflow will be expectedly high (e.g. Amucha gully, NjabaWS1, IdeatoNorth1, Isu_gully1, Isu_gully2, Isu_gully3, Njaba4, Orlu2, Urualla_gully1, Urualla_gully2, Urualla_gully3). Therefore, while increase in connectivity of non-vegetated surfaces will mostly likely increase surface runoff, gully control methods should also involve controlling lateral flow, especially, on gully-adjacent sub-basins. Engineering

structures designed to carry surface flow away from gullies, as well we use of tree-planting which would initiate transpiration may help stabilise the gullies.

3. Gully growth in spite of increased vegetal cover in the catchment: sustained gully growth notwithstanding increased tree-cover within a catchment but especially on gully-adjacent sub-basins indicates possibility of sub-surface erosion and groundwater-driven landsliding. In such gully catchments, if the sub-basins are dominated by lower slope angles, then lesser lateral flow and higher groundwater contribution to streamflow will be expected. Gully management involving controlling surface flow only maybe of little significance. Reducing the groundwater level may possibly enhance gully stability (Egboka & Nwankwor, 1985). Tree weight especially where the plant is found at the boundary between gentle and steep slope and transmission of kinetic energy from trees into gully slopes increase propensity to landsliding (Gao et al. 2020). Also, tree roots create local channels for enhanced infiltration which potentially increases pore pressure and thereby increasing slope susceptibility to failure.

   Complete removal of vegetal cover, to reduce adverse effects of trees may facilitate surface runoff erosion and therefore exacerbate the gullying problem. Therefore, replacing trees with grasses whose root systems are deep, fibrous, and made up of dense network e.g. vetiver (*Chrysopogon zizanioides*) and lemongrass (*Cymbopogon citratus*) are favoured as gully-control on gully-adjacent sub-basins. Grasses potentially reduce erosive runoff flow into gullies (Stokes et al. 2008) thereby controlling surficial erosion of gully walls, they are not as heavy as trees thus, less vegetal weight is added to the slope (Wang et al. 2016; Gao et al. 2020), and finally, transmission of destructive kinetic energy into gully slopes by grasses may not be significant in destabilizing gully slopes. Selecting native plants will increase the success of planting program aimed at controlling gullying (Norris et al. 2008; Frankl et al. 2021).

4. Where there is gully growth despite increased vegetal cover and sub-basins are dominated by higher slope angles, especially, in gully-adjacent sub-basins, then lateral flow into gullies will be expectedly high (e.g. IdSouthWS1, NjabaWS1). Reducing lateral flow into gullies should be a priority. Use of sub-surface dams which involved insertion of geomembranes to depths between 0.3 – 2.3 m below the surface have been adopted for gully stabilisation in Northern Ethiopia (Frankl et al. 2016). Although part of the aim of the sub-surface dam was to block bypass flow in soil pipes near the check dam (gabion check dams were constructed to stabilise the gully heads), adopting a

similar technique with some modifications such that lateral flows into gullies are collected in sub-surface dams and pumped out, will potentially reduce gully expansion.

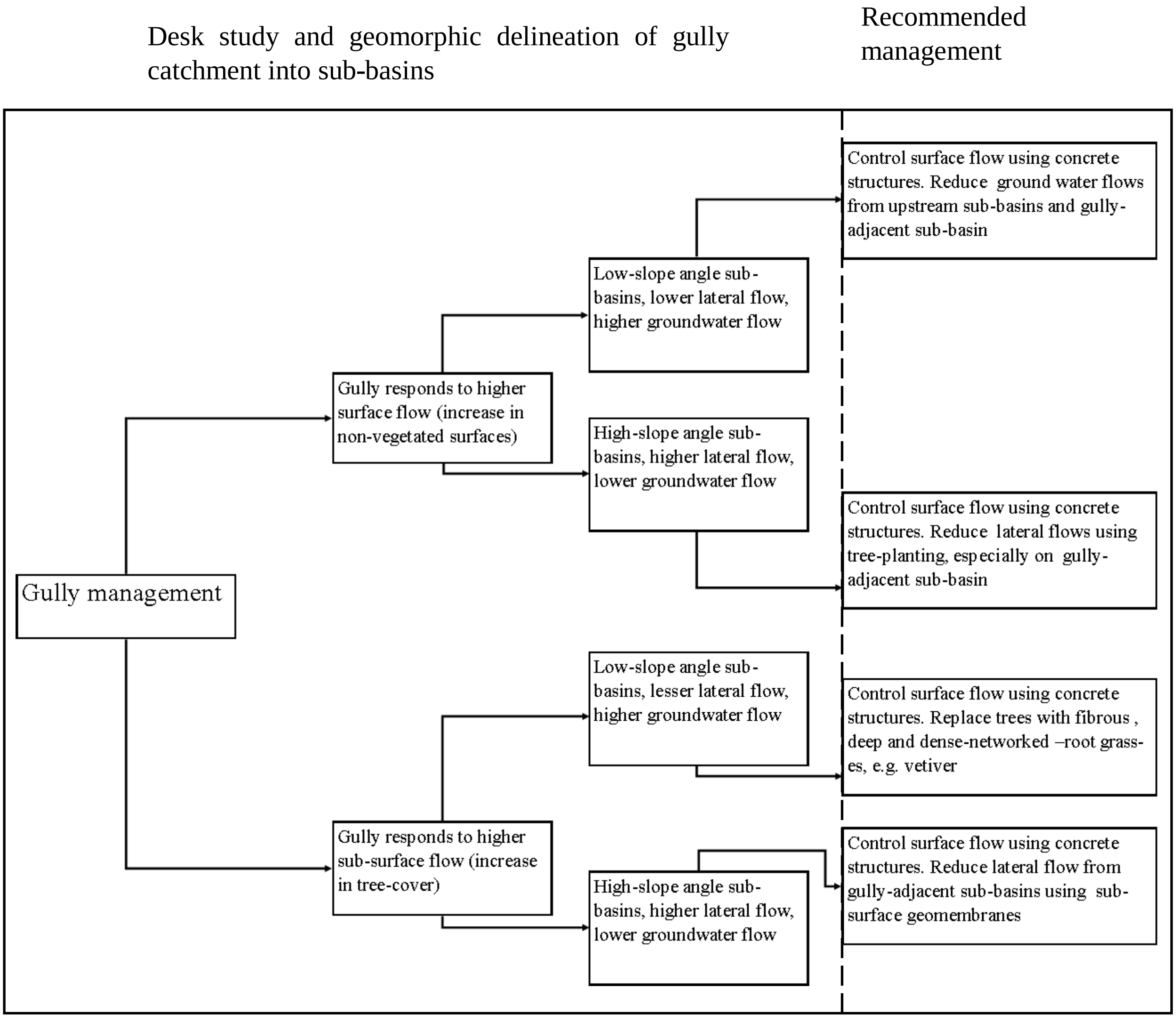

Figure 8.2: Decision tree of recommended gully-management. Two main phases are identified, initial desk study and geomorphic definition of sub-basins, and recommended gully-management.

The main challenge with the enumerated points is that gullies in the study area behave differently from one another based on uniqueness of individual gully catchments. Secondly, depending on the stage of evolution of a gully (Betts et al. 2003; Okagbue & Uma, 1987), one recommended method may be insufficient, rather, combinations of different approaches. For example, there may be increase in non-vegetated areas over the years which translates to higher surface flow into a gully, however, same gully might have attained an advanced stage, such that controlling surface flow alone may not be sufficient because of influence of groundwater-driven mass movement. In conclusion therefore, effective gully control must acknowledge the significance of gully catchment uniqueness as what works in one catchment is not guaranteed to work in another, despite similarities in physical factors such as elevation and soil. Similarly, a successful control measure for one gully may not be successful for another gully depending on the stage of evolution of the gully.

For gully management, two routes can be adopted to replicate this research and adopt the best management practice in a catchment: Firstly by conducting simple hydrological modelling. The data (e.g. DEM and satellite data) and hydrological model (SWAT) used in this work are open source and freely available. While ArcGIS is not free, there is a version of the SWAT model available on open source platforms such as QGIS and R-Studio. Secondly, with the availability of a DEM, a catchment can be delineated into sub-basins while analysis of vegetal cover changes is carried out. Inferences on hydrological dynamics can be drawn from this second approach and inform the best management approach to adopt for a gully of interest.

8.4 Summary and Conclusions

The conceptual model presented in figure 2.3 formed the basis for formulating research questions in this study. While the factors considered in figure 2.3 were important, new factors of interest in gully-landslide studies have been found to be significant in the study area (figure 8.1). Research results have also shown that gully-landslide interactions are driven by multiple ecogeomorphic factors whose interactions with one another are ever dynamic. Hence, in providing solutions to environmental problems, the pursuit of multiple driving factors is favoured over the search for a single driving factor. Interactions among ecogeomorphic drivers of gully-landslide linkages enhance the difficulty of applying a single gully-management project across an entire area, notwithstanding similarities in land use, topography, and climate. It has been recommended that any successful gully-control project must acknowledge the uniqueness of different gully watersheds and treat gullies as individual entities and management methods should not be generalised across all gullies.

Chapter 9

Conclusions

9.0 Introduction

This chapter concludes the thesis. References are made to the aim of the thesis, to improve understanding of ecogeomorphic processes that influence the interactions between gully erosion and landslides in the Orlu region of southeast Nigeria. Key findings of this research and wider implications of these findings are presented and recommendations for future research are suggested.

9.1 Key findings of the study and wider implications

To achieve the aim of this research, four objectives were set in chapter 1 while multi-method research techniques which involved combinations of analysis of remotely sensed data, quantitative and qualitative research methods, geotechnical survey and hydrological modelling were adopted. In a data-scarce region, such as southeast Nigeria, multi-method research approach as adopted in this research provided answers to previously unreported findings. For example, the dates of gully initiation in the Orlu area, and the role of civil war as the primary driver of gullying. Combinations of both quantitative and qualitative methods are not common (Nyssen et al. 2006; Frankl et al. 2016) and this is the first time combination of these research methods is used in a single research project related to gully erosion and landsliding in southeast Nigeria. Research findings are summarised into the following:

9.1.1 Civil war as a gully-driver in southeast Nigeria

The Nigeria-Biafra civil war (1967-1970) was the beginning for gully initiation in the Orlu region of southeast Nigeria. While military activities such as digging trenches, which facilitated gullying in the late 1960s no longer exist today, increase in demographic pressure which led to removal of natural vegetation cover is very much present and is likely the current driver of gullying in the study area. This study is the first study to recognise The Nigerian civil war as a gully-driver in southeast Nigeria.

9.1.2 Uniqueness of gully catchments and implications for gully management

Results obtained from chapters 4 and 5 suggest the importance of treating individual gully catchments as separate entities despite similarities in factors such as topography, climate, and soil. It was shown in chapter 4 that at the regional scale, while reduction in fallow-cover over a certain period is possible, at the catchment level, increase in fallow-cover within some gully catchments is feasible. Results in chapter 5 indicate that at the catchment scale, variations in vegetal-cover distribution are also possible, for example, while the upstream sections of a catchment may experience increased forest-cover, the gully head and gully-adjacent lands may be covered by non-vegetated surfaces or vice versa. These regional and catchment-scale changes in land cover have implications for driving processes of gullying and gully-management practices, and therefore reaffirms the need for catchment-specific control for gullies due to uniqueness of gully watersheds.

9.1.3 Surface and sub-surface flows as agents of gully-landslide interactions

The high sandy nature of soils in the study area predisposes them to dispersal by rainwater and surface runoff, high infiltration, and seepage erosion (Obi & Asiegbu, 1980; Okagbue & Ezechi, 1988). Increased non-vegetated surfaces due to land-use changes lead to higher volumes of surface runoff which enhances rill incision and surficial erosion. When the slopes of rills cross critical thresholds, gully-induced slides occur and thus enlarging the sizes of the gullies. On gully sections where slides occur, there is reduction in vegetal cover which further propagates the role of surface runoff as an agent of landslide-induced gully expansion. Increased vegetal cover enhances high infiltration and facilitates effects of groundwater as an agent of landsliding which leads to gully expansion.

9.1.4 Surface and sub-surface flows as agents of gully-landslide interactions: implications for gully-control techniques

This study has shown that in gully control, both surface and sub-surface processes should be considered in the design of appropriate mitigating technique. Reliance on techniques designed to control surface flow alone will not be efficient in controlling sub-surface flow. As noted by focus-group attendees, gully-induced landslides occur after rainfall and suggests the role of groundwater as a landslide-initiator. Modelling results supported this observation by the villagers. Controlling sub-surface flow alone may also not be efficient considering increases in non-vegetated surfaces and volume of surface runoff across the region. Finally, in the design of gully-control methods, a good knowledge of the ecogeomorphic interactions in a gully catchment is important in choosing management practices. The novelty of the multi-method approach adopted in this research has led to these conclusions and therefore highlights the significance of adopting combinations of research methods in geomorphological studies.

9.1.5 Direct and indirect effects of gullying

Participants at focus group meetings, questionnaire survey respondents and interviewees identified effects of gullying on their lives and livelihood. While it was easier to relate with direct effects (e.g. loss of farmland, loss of houses/property), this study recognised indirect results of gullying which could have implications in the future (e.g. prolonged emission of greenhouse gases and unavailability of seedlings for planting). Increase in population and population density and reduction of arable lands for farming have forced villagers to cultivate marginally stable lands despite associated hazards.

9.2 Suggestions for future research

The adoption of combinations of hydrological modelling, qualitative and quantitative research techniques, geotechnical survey and analysis of remotely sensed data in a data-scarce region such as southeast Nigeria has proved very useful. Results from chapter 7 showed the perception to gully-landslide hazards, community knowledge of driving forces and local methods of controlling gullying. Incorporating these local ideas to scientific knowledge will boost understanding of processes, lead to a comparison of local knowledge and scientific findings and inform design of control processes (Callon, 1999). It will be helpful to see future studies adopt combinations of these research techniques to further improve knowledge on gullying in other gully-prone areas.

Often, the goal of research is to improve lives and livelihood. This goal is achieved when a good knowledge of forcing factors of the research problem are identified. The primary aim of the present research was to understand processes of gully-landslide interactions. Based on research findings, some gully-control methods were advocated but have not been tested. It would be useful to know the efficiencies of these suggested management-methods in gully catchments that satisfy the conditions. Physical modelling or field experiments with the aim of understanding gully response to suggested management-techniques will lead to adoption or modification of these techniques. Physical modelling can be achieved in a laboratory setting where gully driving processes and gully-control recommendations are simulated. Field experiments can be achieved in an un-managed gully that satisfies the conditions of the research recommendations.

Use of hydrological modelling to recognize hydrological response of gully catchments to environmental changes is beneficial in understanding likely processes that drive gully erosion. In a data-scarce region like southeast Nigeria where data on surface and sub-surface flows are not readily available, hydrological models help improve understanding of surface and sub-surface flows. Modelling results suggested hydrological variations in gully catchments and these variations might be likely reasons a single gully-management technique may not be efficient across the entire region, a view held by previous studies (e.g. Okagbue & Uma, 1987). For future research, it would be useful to use a model that simulates gully erosion and different gully control measures. Adopting such models will improve understanding of driving processes of gullying with the ultimate goal of improving gully-control and reducing associated hazards and risks.

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Appendices

Appendix 4.1: Summary changes in gully sizes for catchments captured in the 2009, 2014 and 2018 satellite data.

Catchment	Change in length 2009 – 2014 (m)	Change in width 2009 – 2014 (m)	Change in area 2009 – 2014 (m^2)	Change in gully length 2014 – 2018 (m)	Change in gully width 2014 – 2018 (m)	Change in gullied area 2014 – 2018 (m^2)
IdNorthWS	0	3.98	397.53	10	6.10	947.50
IdSouthWS1	40	-3.53	1055.76	0	-1.61	-346.52
Ideatosouth_gully 1	NA	NA	NA	600	31.07	19892.18
Ideatosouth_gully2	360	12.3	5060.38	200	11.10	8472.19
Ideatosouth3	100	10.9	1101.59	90	3.61	1748.31
Isu_gully1	104	-4.00	4213.13	12	12.30	4213.13
Isu_gully2	6	7.84	2198.99	20	4.86	3767.95
Isu_gully3	0	0	0	170	18.6	9937.78

Appendix 4.2: Summary changes in gully sizes for catchments captured in the 2009 and 2018 satellite data.

Catchment	Change in gully length 2009 – 2018 (m)	Change in gully width 2009 – 2018 (m)	Change in gullied area 2009 – 2018 (m^2)
NjabaWS1	0	6.11	4204.54
Amucha	200	13.05	19954.82
IdeatoNorth	0.00	13.84	13999.81
IdeatoNorth1	40	-1.73	5659.22
Njaba2	-100	13.09	776.76
Njaba4	200	8.06	6421.85
Njaba5	500	18.37	10008.44

Orlu1	600	11.70	28236.74
Orlu2	80	-0.97	1991.54
	360	20.00	24547.77
Urualla_gully1	100	0.2	13917.61
Urualla_gully2	340	2.5	7001.27
Urualla_gully3	50	13	13999.8
Obibi-Ochasi	500	50.69	23192.34
Umueshi	40	6.5	3029.22

Appendix 4.3: Multiple regression result for gully length, p-value = 0.04, r2 = 0.43, adjusted r2 = 0.33, n = 14, Years of study = 2009 – 2018.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	141.28	55.80	2.53	0.03
Non-veg	180.06	82.09	2.19	0.05
Tree	106.96	64.52	1.66	0.13

Appendix 4.4: Multiple regression result for gully width, p-value = 0.94, r2 = 0.01, adjusted r2 = -0.17, n = 14, Years of study = 2009 – 2018.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	11.80	4.22	2.79	0.02
Non-veg	0.49	6.21	0.07	0.93
tree	-0.04	4.88	-0.00	0.99

Appendix 4.5: Multiple regression result for gullied area, p-value = 0.09, r2 = 0.34, adjusted r2 = 0.23, n = 14, Years of study = 2009 – 2018.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	11917.26	2354.58	5.06	0.00
Non-veg	8312.933	3463.38	2.40	0.03
tree	6252.079	2722.18	2.29	0.04

Appendix 4.6: Multiple regression result for gully length, p-value = 0.94, r2 = 0.03, adjusted r2 = -0.46, n = 7, Years of study = 2009 – 2014.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	88.86	79.66	1.11	0.32
Non-veg	268.83	971.72	0.27	0.79
tree	357.29	1643.99	0.21	0.83

Appendix 4.7: Multiple regression result for gully width, p-value = 0.51, r2 = 0.29, adjusted r2 = -0.07, n = 7, Years of study = 2009 – 2014.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.65	3.55	0.46	0.66
Non-veg	1.12	43.35	0.02	0.98
Tree	-21.95	73.35	-0.29	0.77

Appendix 4.8: Multiple regression result for gully area, p-value = 0.93, r2 = 0.04, adjusted r2 = -0.44, n = 7, Years of study = 2009 – 2014.

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2299.44	1198.68	1.91	0.12
Non-veg	2073.57	14620.53	0.14	0.89
Tree	5661.31	24735.45	0.22	0.83

Appendix 4.9: Multiple regression result for gully length, p-value = 0.86, r2 = 0.06, adjusted r2 = -0.32, n = 8, Years of study = 2014 – 2018.

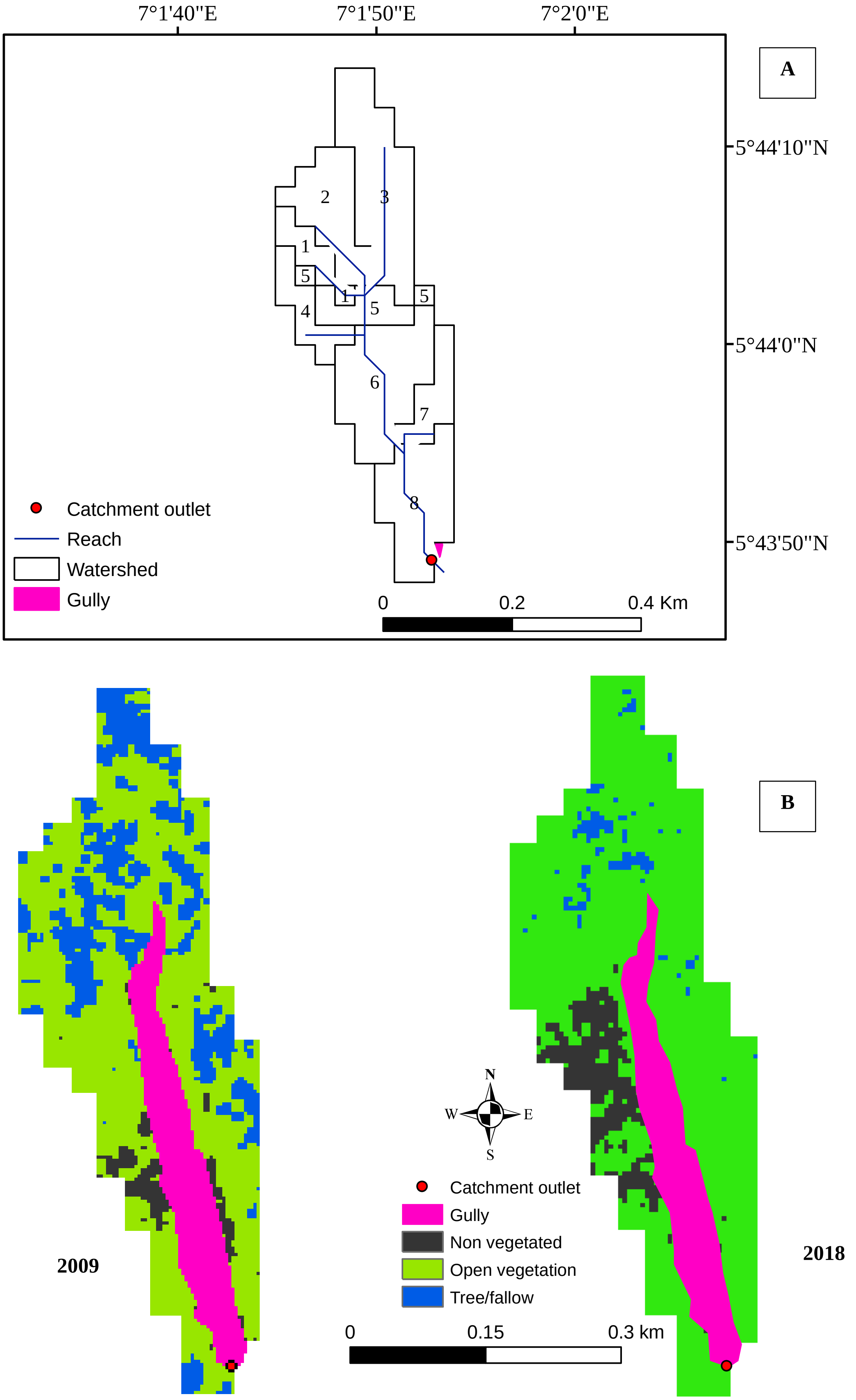
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	163.45	96.78	1.68	0.15
Non-veg	1245.44	3394.08	0.36	0.72
Tree	558.81	1123.61	0.49	0.64

Appendix 4.10: Multiple regression result for gully width, p-value = 0.58, r2 = 0.2, adjusted r2 = -0.12, n = 8, Years of study = 2014 – 2018.

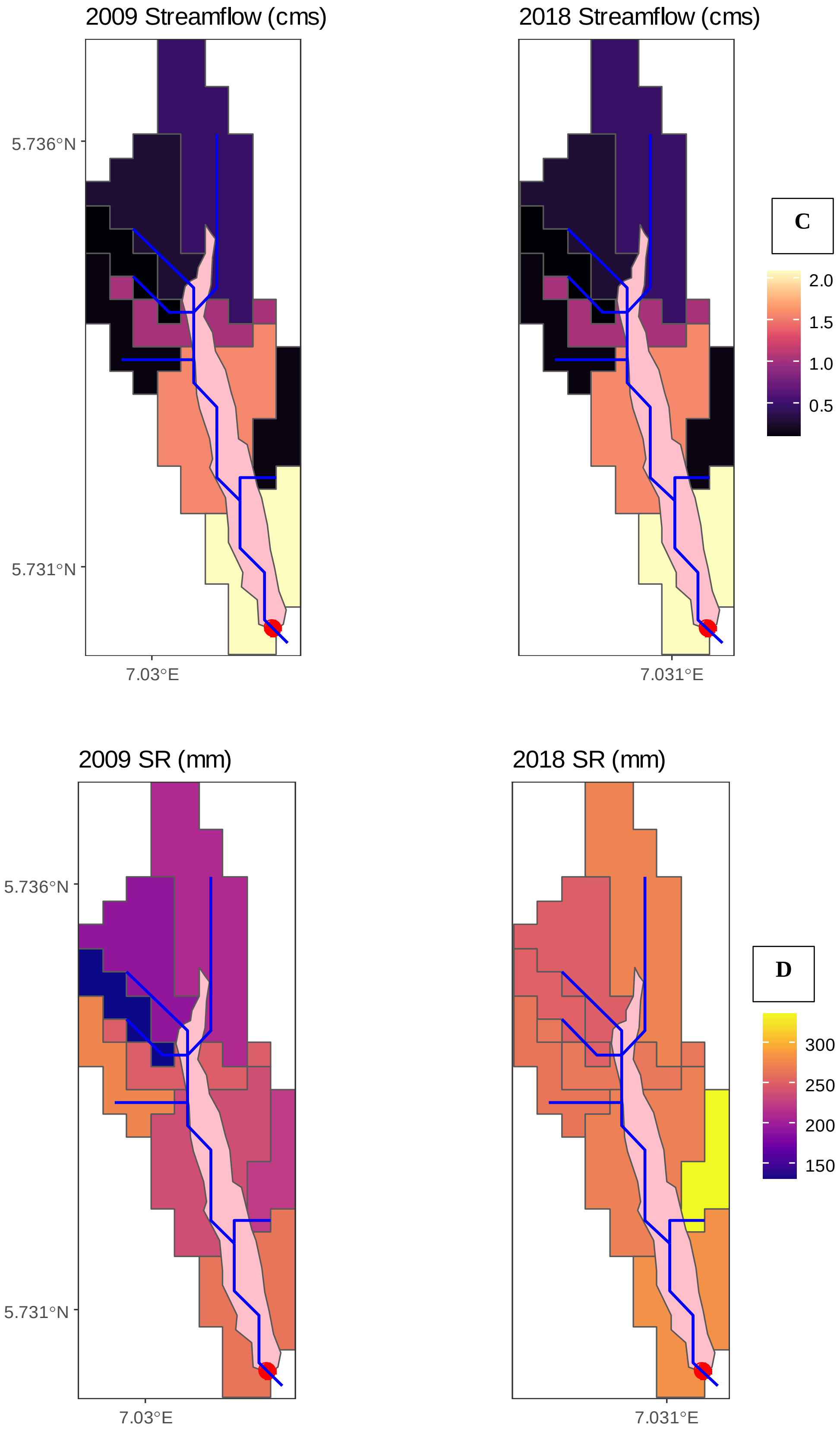
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	13.16	4.53	2.90	0.03
Non-veg	118.91	158.96	0.74	0.48
Tree	52.35	52.62	0.99	0.36

Appendix 4.11: Multiple regression result for gully width, p-value = 0.56, r2 = 0.2, adjusted r2 = -0.11, n = 8, Years of study = 2014 – 2018.

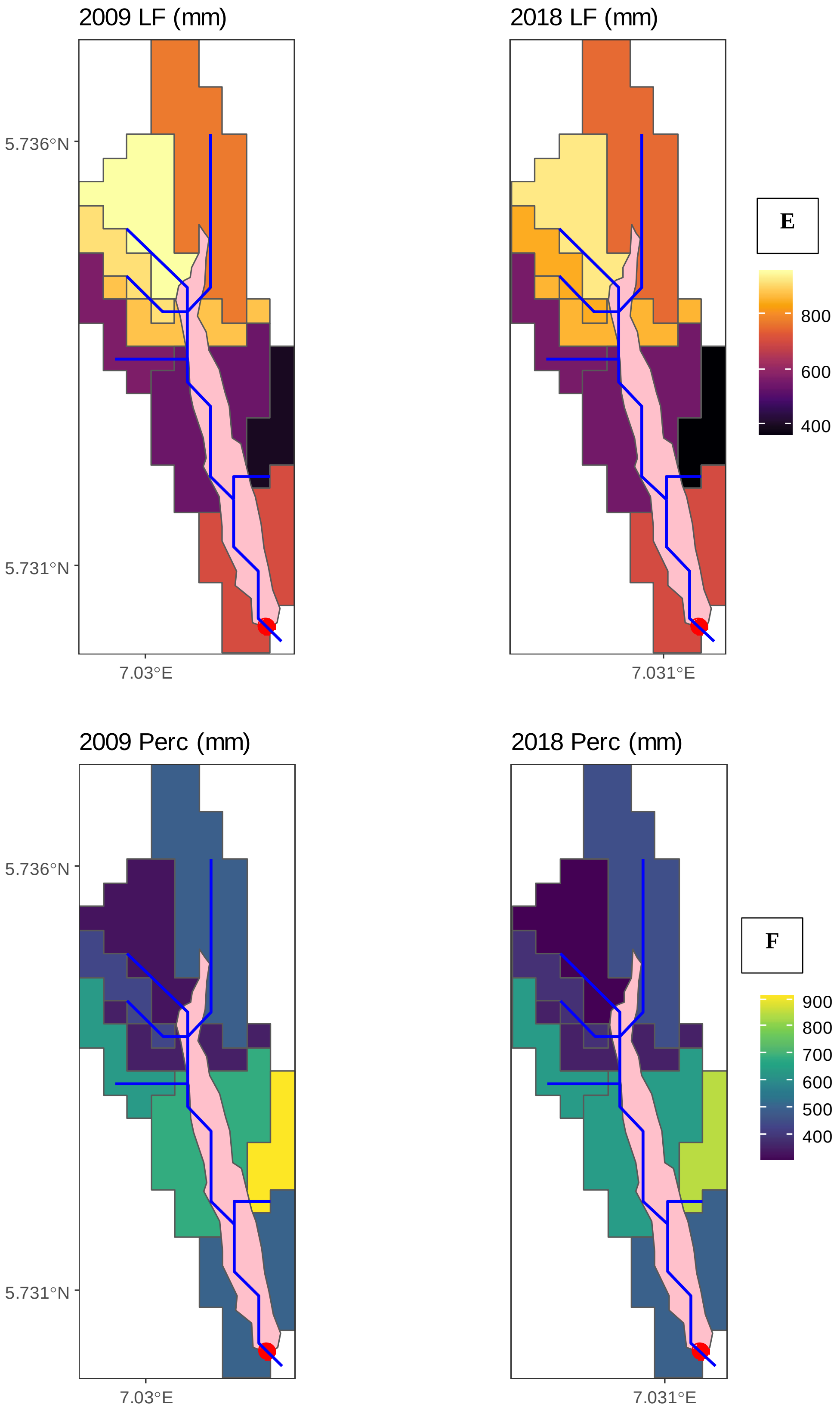
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	7665.72	2905.52	2.63	0.04
Non-veg	79162.13	101893.9	0.77	0.47
Tree	34477.93	33732.07	1.02	0.35



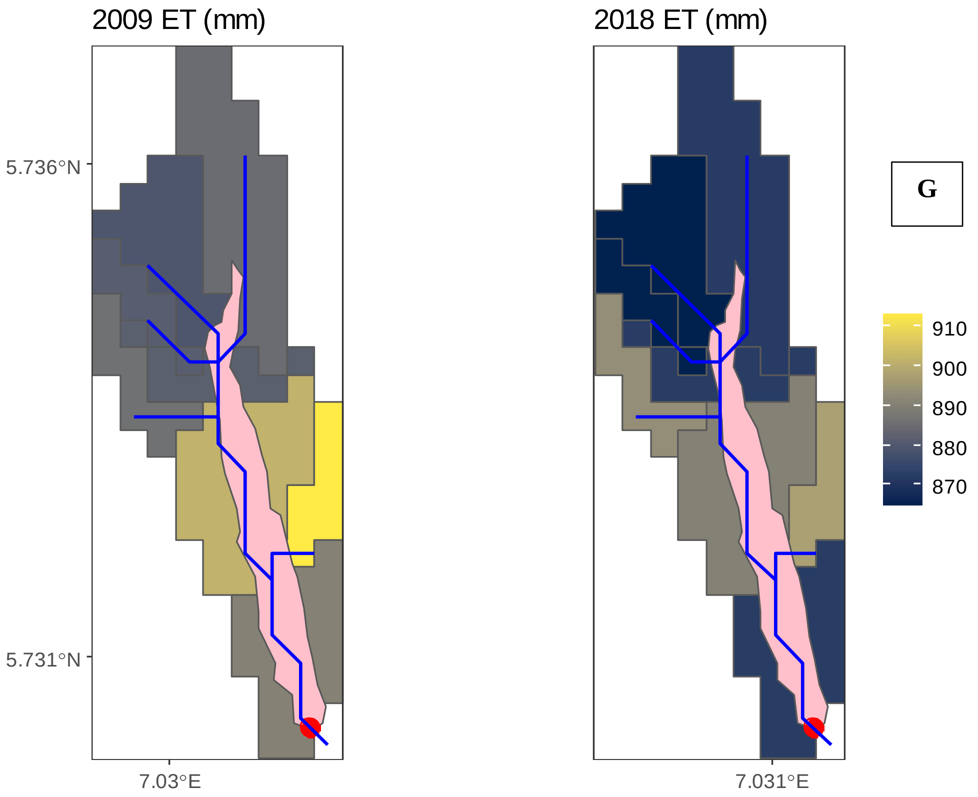
Appendix 5.1: NjabaWS1 gully watershed.



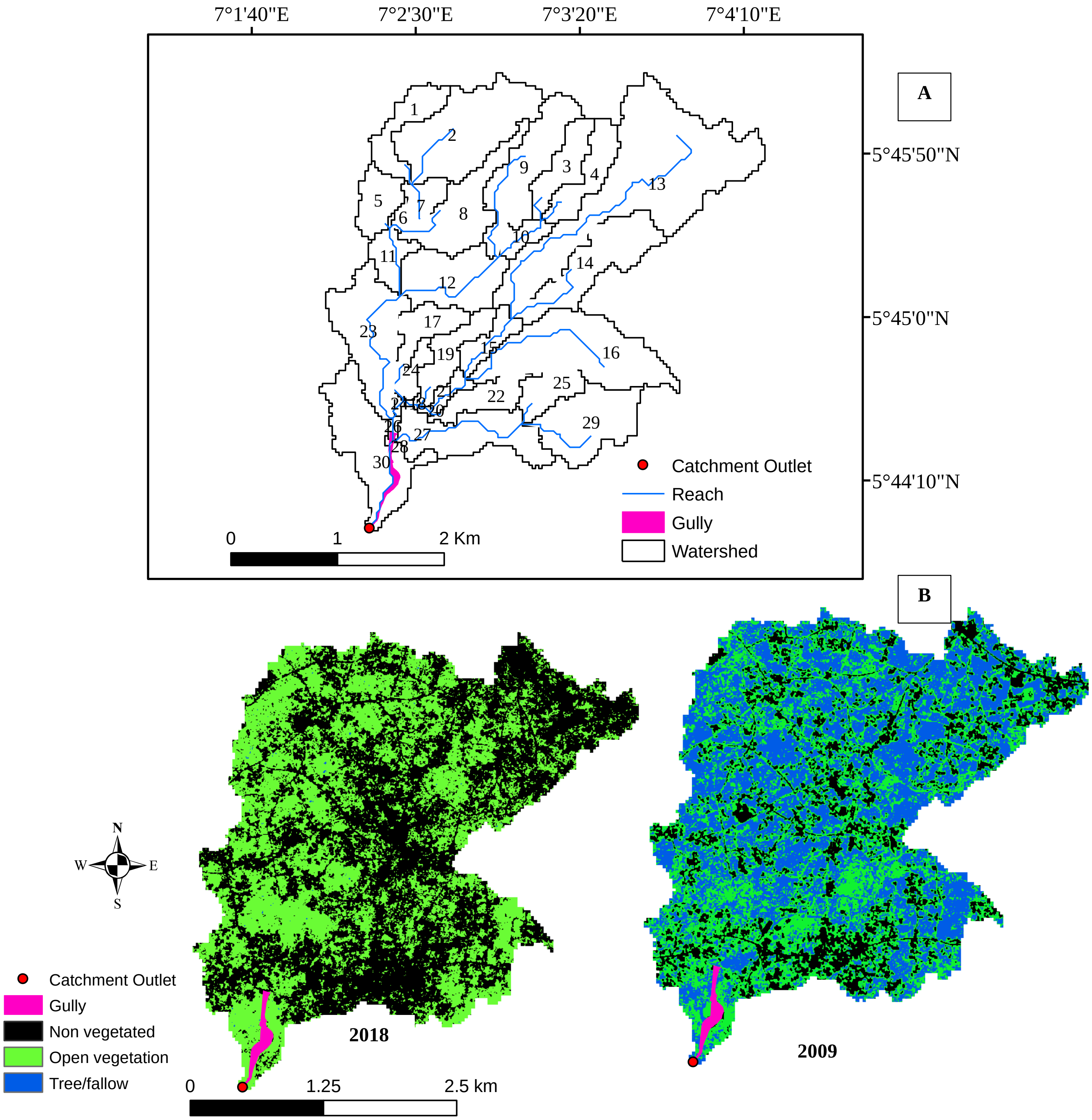
Appendix 5.1 cntd: NjabaWS1 gully watershed.



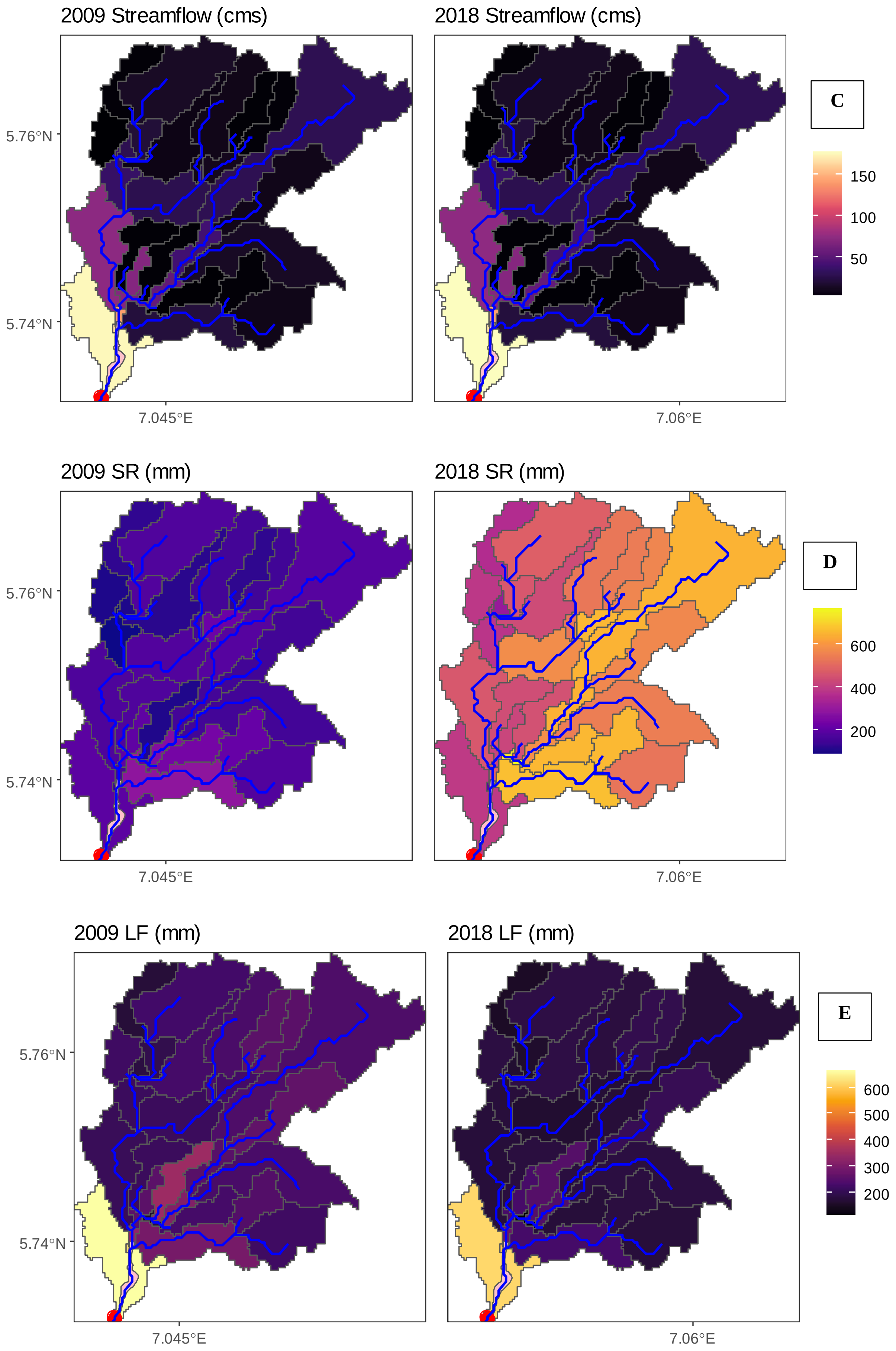
Appendix 5.1 cntd: NjabaWS1 gully watershed.



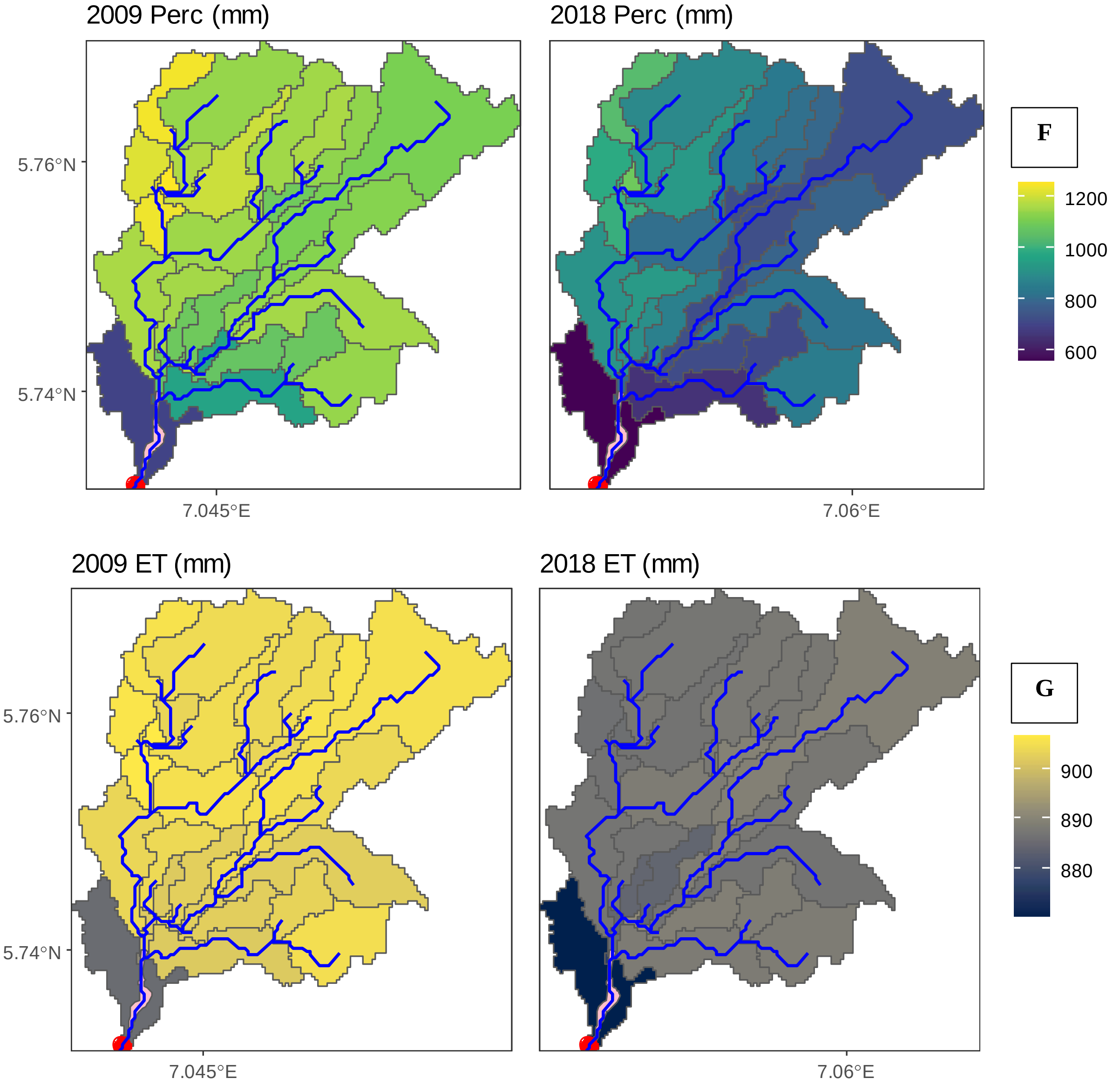
Appendix 5.1 cntd: A, NjabaWS1 gully watershed. Gully ID, 4. B, Land use change between 2009 and 2018 showing reduction fallow area. Non-vegetated area remained at low-density between 2009 and 2018. C, streamflow estimates. Maximum streamflow remained the same at 2 m^3/s. D, surface runoff contribution to streamflow showing increased runoff with higher open-vegetation and reduction in fallow. E, lateral flow showing reduction in all but sub-basin 6 between 2009 and 2018. F, Percolation. Increase in percolation was estimated for sub-basins 4 and 5 in 2018, the other sub-basins experience reduced values for percolation. G, evapotranspiration. 2009 had higher estimates than 2018.



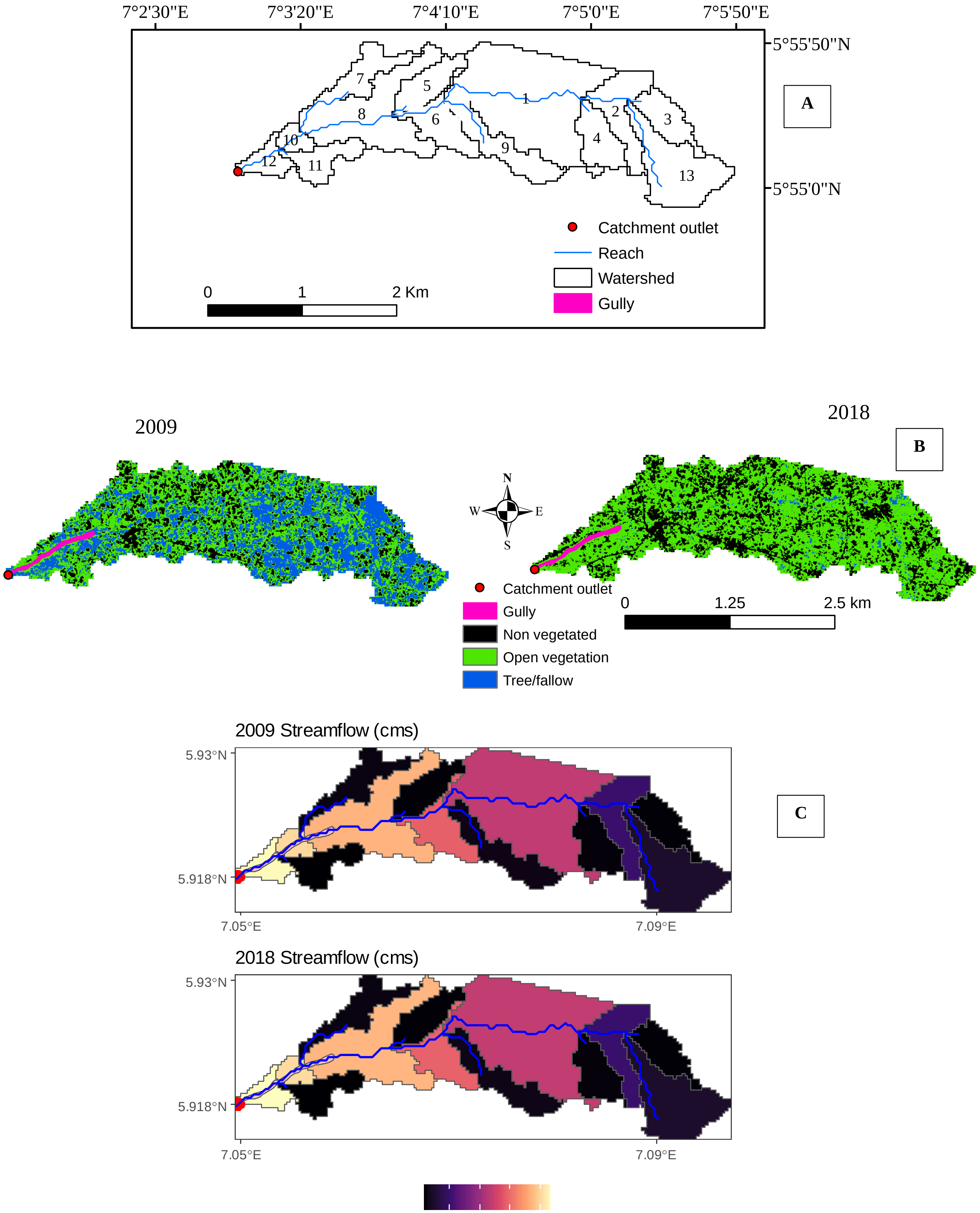
Appendix 5.2: Amucha gully watershed.



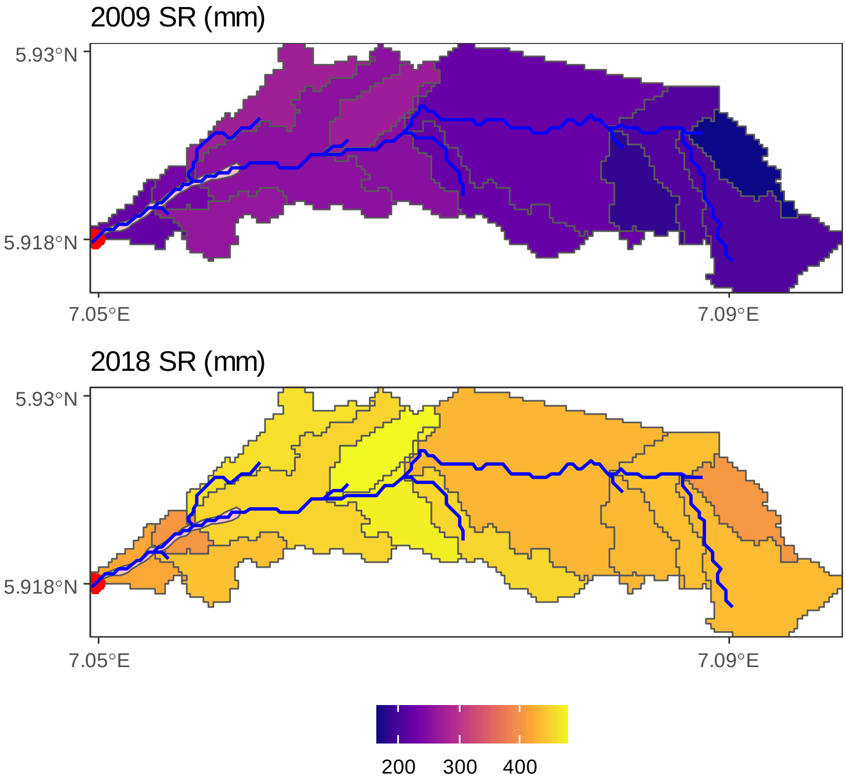
Appendix 5.2 cntd: Amucha gully watershed.



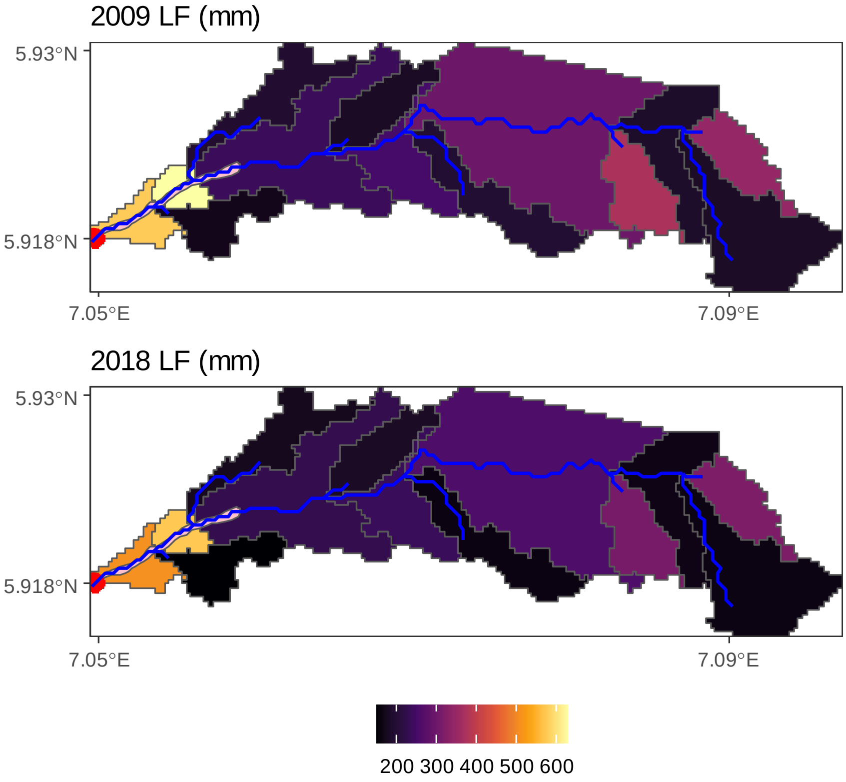
Appendix 5.2 cntd: A, Amucha gully watershed. Gully ID, 5. B, Land use change between 2009 and 2018 showing reduction in fallow and increase non-vegetated area. Non-vegetated area changed from medium density to high density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 178 and 176 m^3/s in 2018 and 2009 accordingly. D, surface runoff contribution to streamflow showing increased runoff with higher non-vegetated surfaces and reduction in fallow. E, lateral flow showing reduction in all sub-basins between 2009 and 2018. F, Percolation. Reduction in percolation is observed across the sub-basins. G, evapotranspiration. 2009 had higher estimates than 2018. 2009 rainfall = 2447 mm and 2443 mm for 2018.



Appendix 5.3: Ideato North gully watershed.



D



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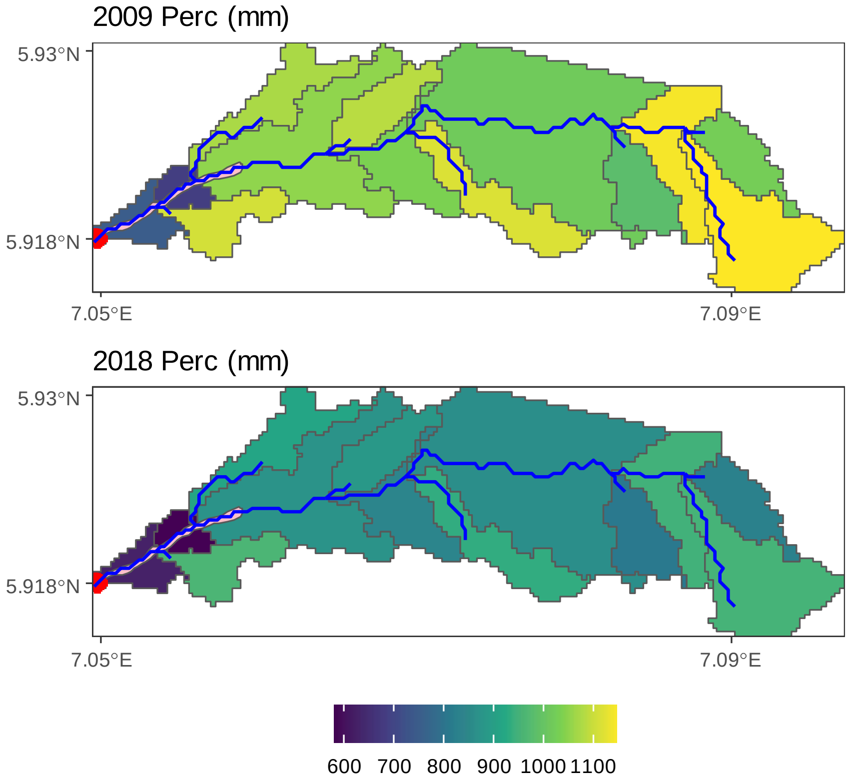
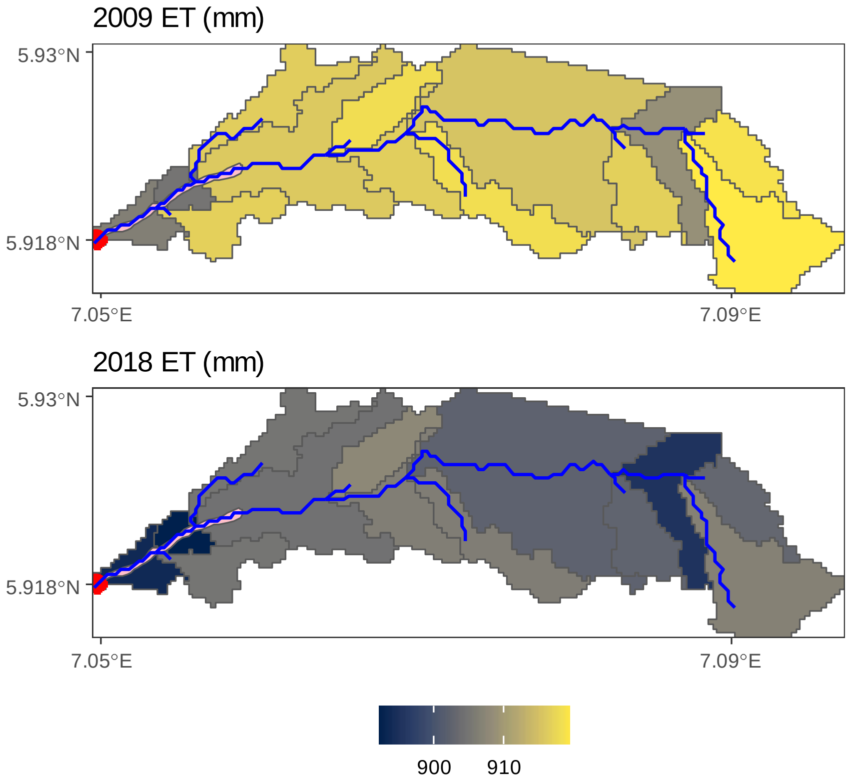
Appendix 5.3 cntd: Ideato North gully watershed.

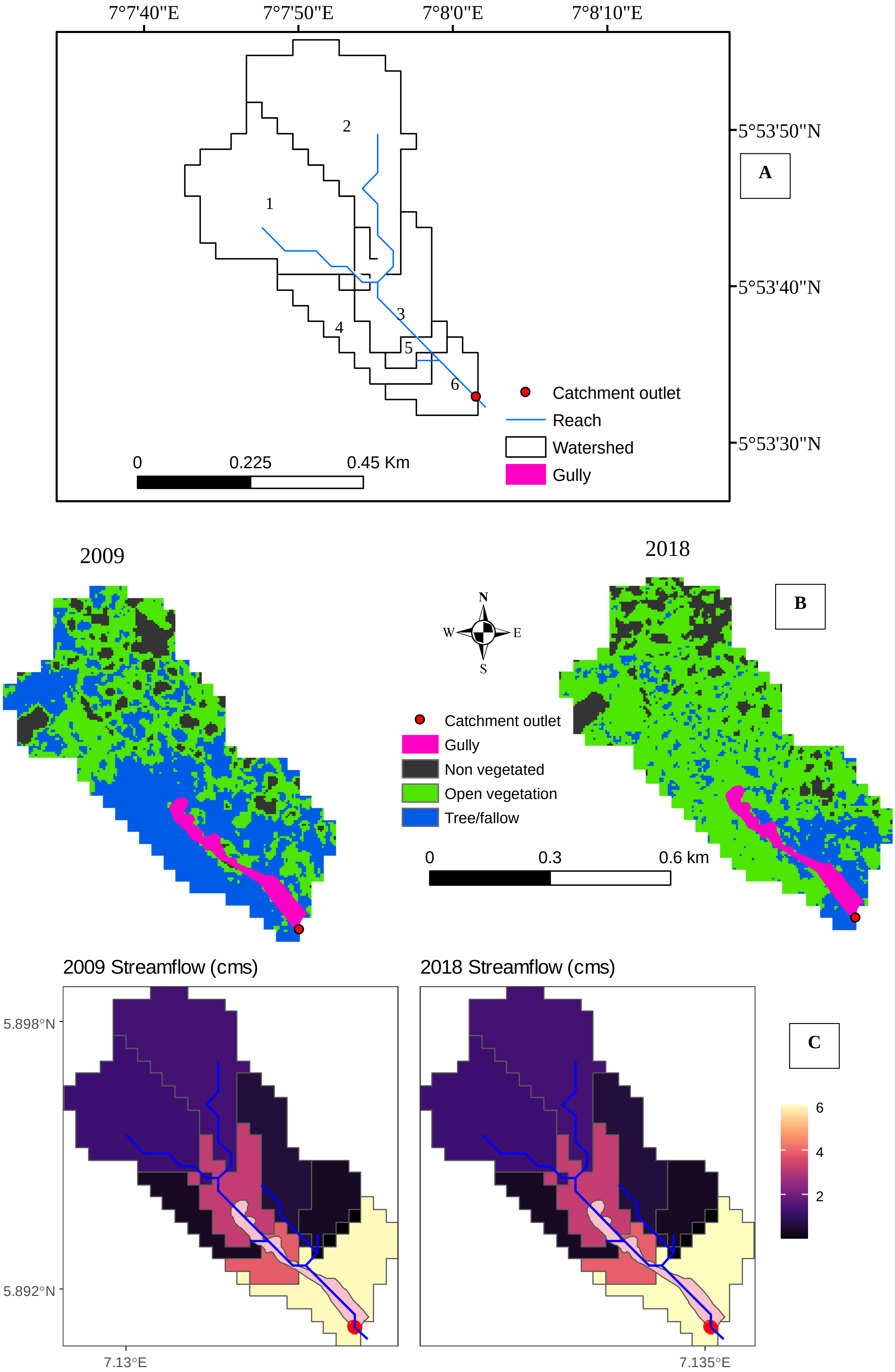


F

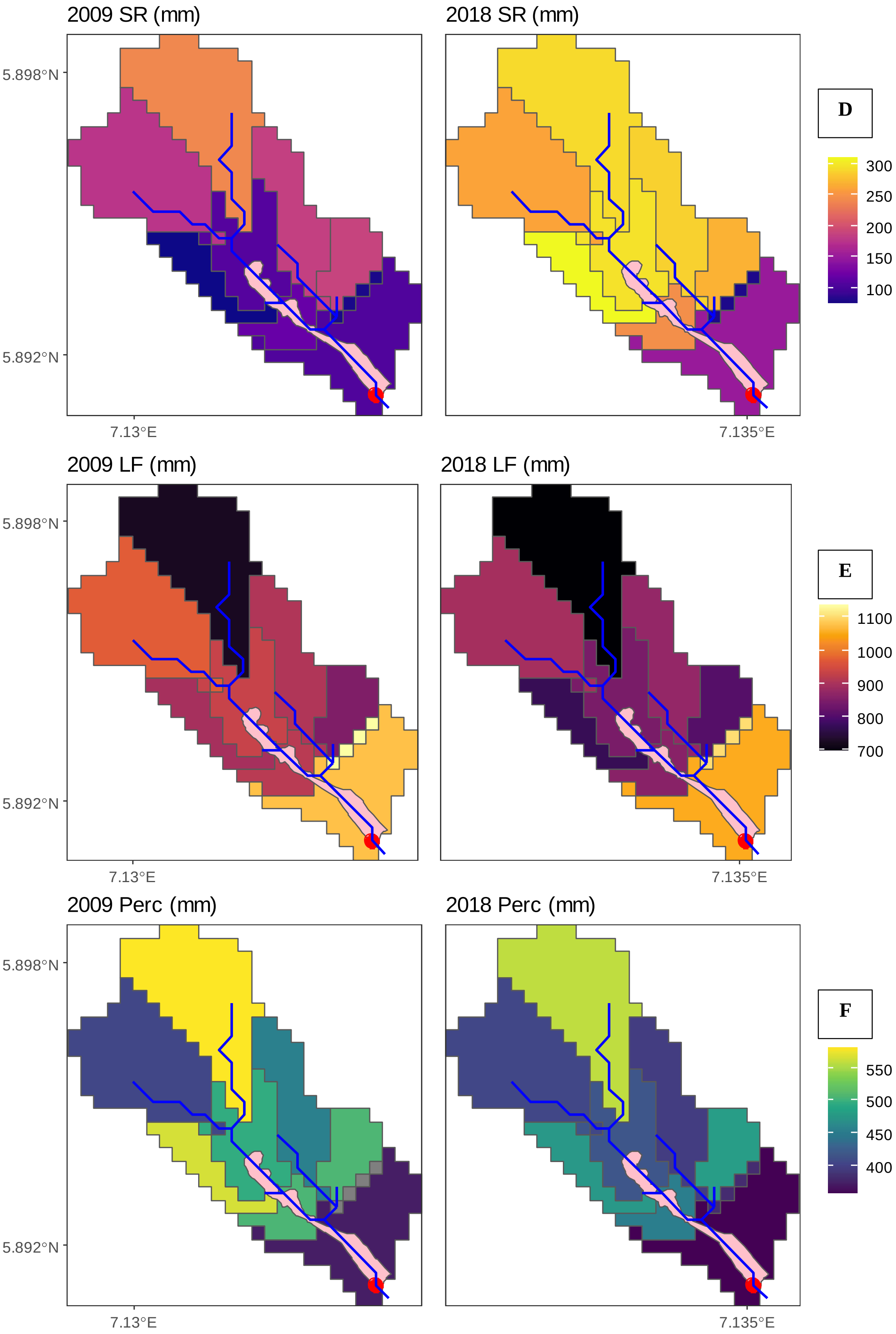


G

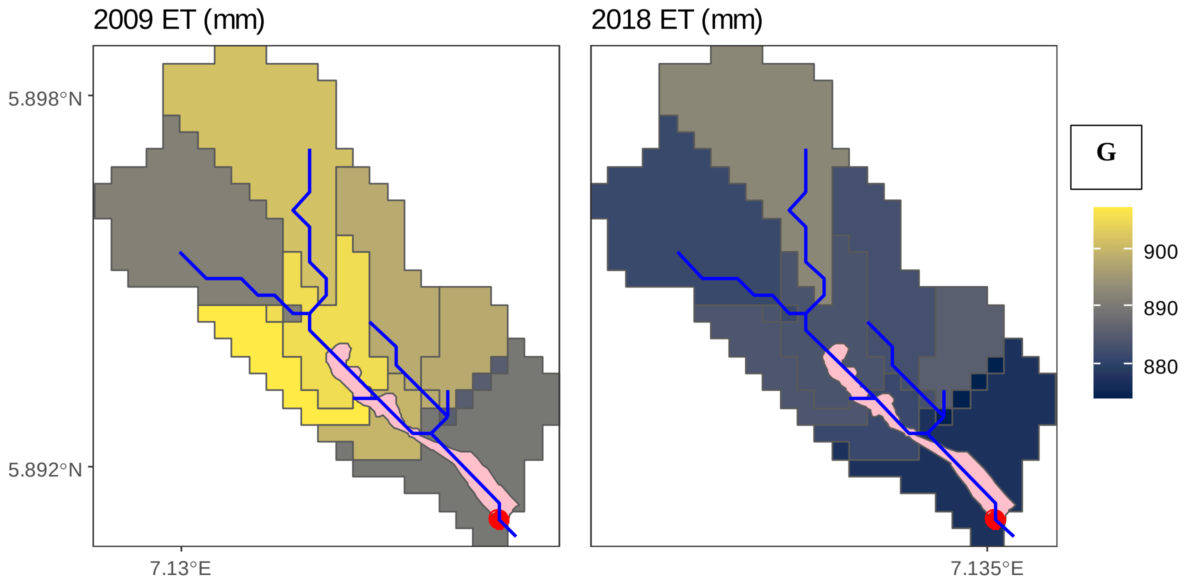
Appendix 5.3 cntd: A, IdeatoNorth gully watershed. Gully ID, 20. B, Land use change between 2009 and 2018 showing increased non-vegetated area. Non-vegetated area changed from low density to high density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 10 m^3/s in 2009 and 2018. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduction in all sub-basins between 2009 and 2018. F, Percolation. Reduction in percolation is observed across the sub-basins. G, evapotranspiration. 2009 had higher estimates than 2018. 2009 rainfall = 2450 mm and 2446 mm for 2018.



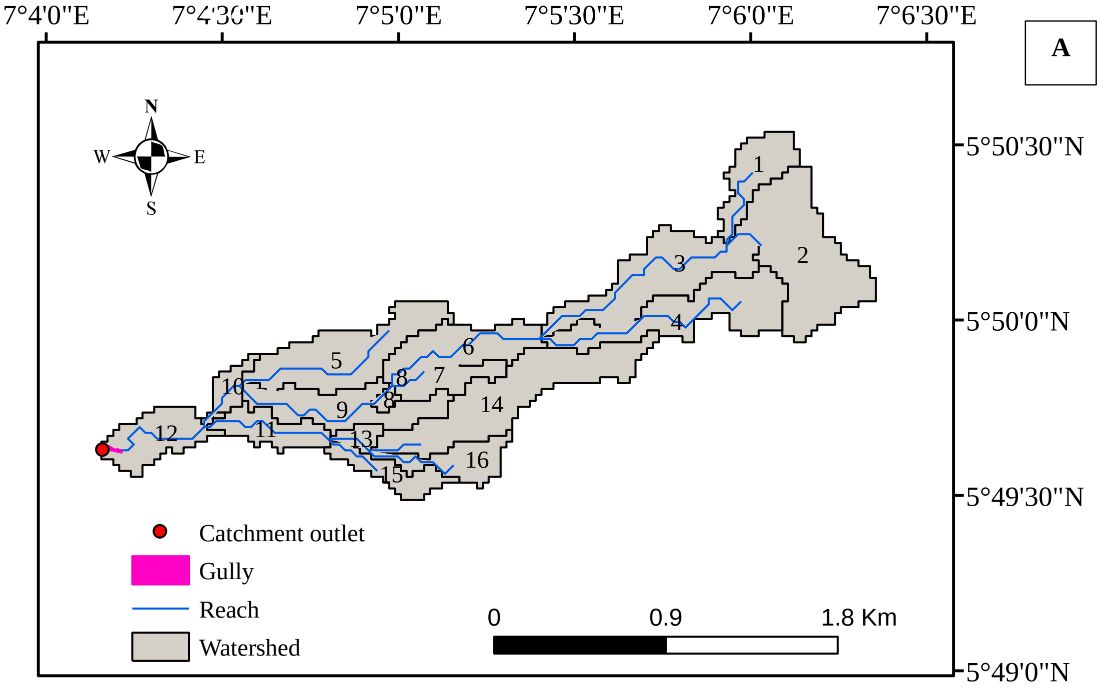
Appendix 5.4: IdeatoNorth1 gully watershed.



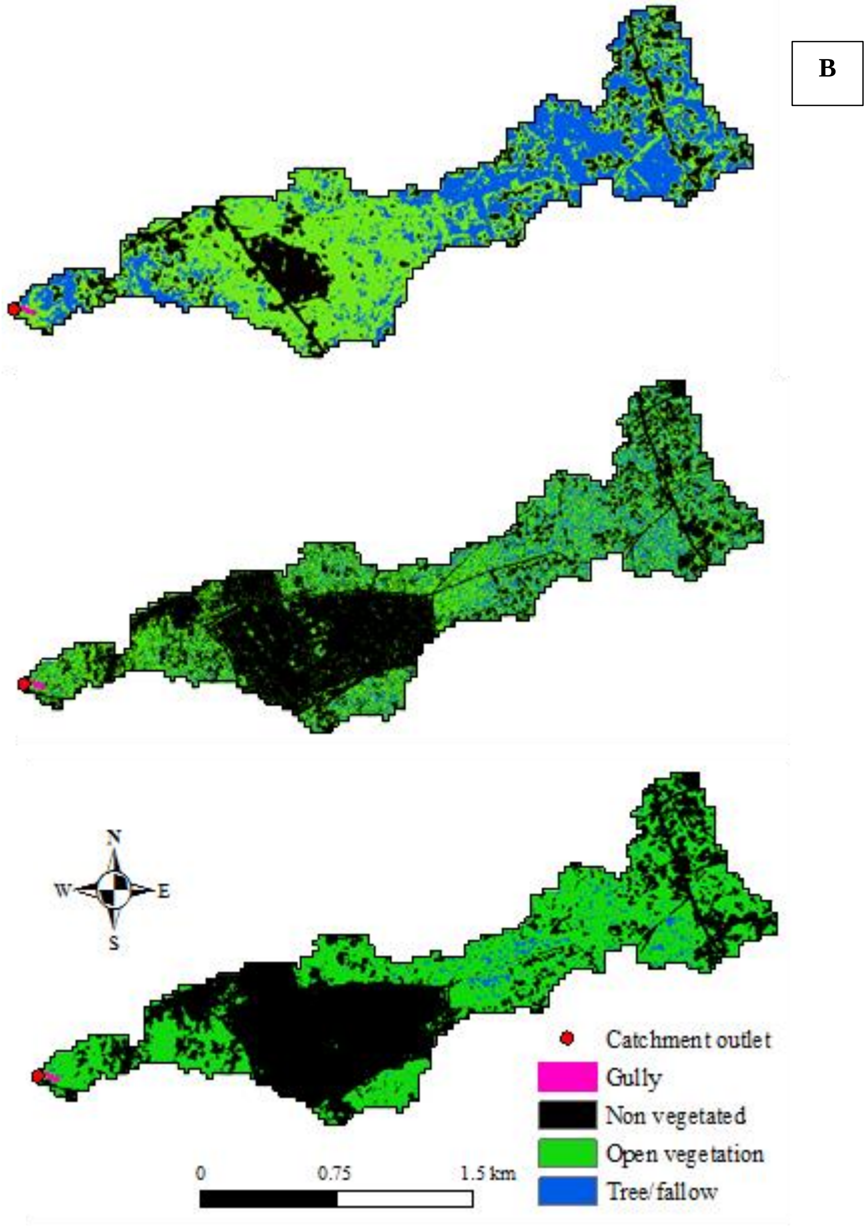
Appendix 5.4 cntd: IdeatoNorth1 gully watershed.



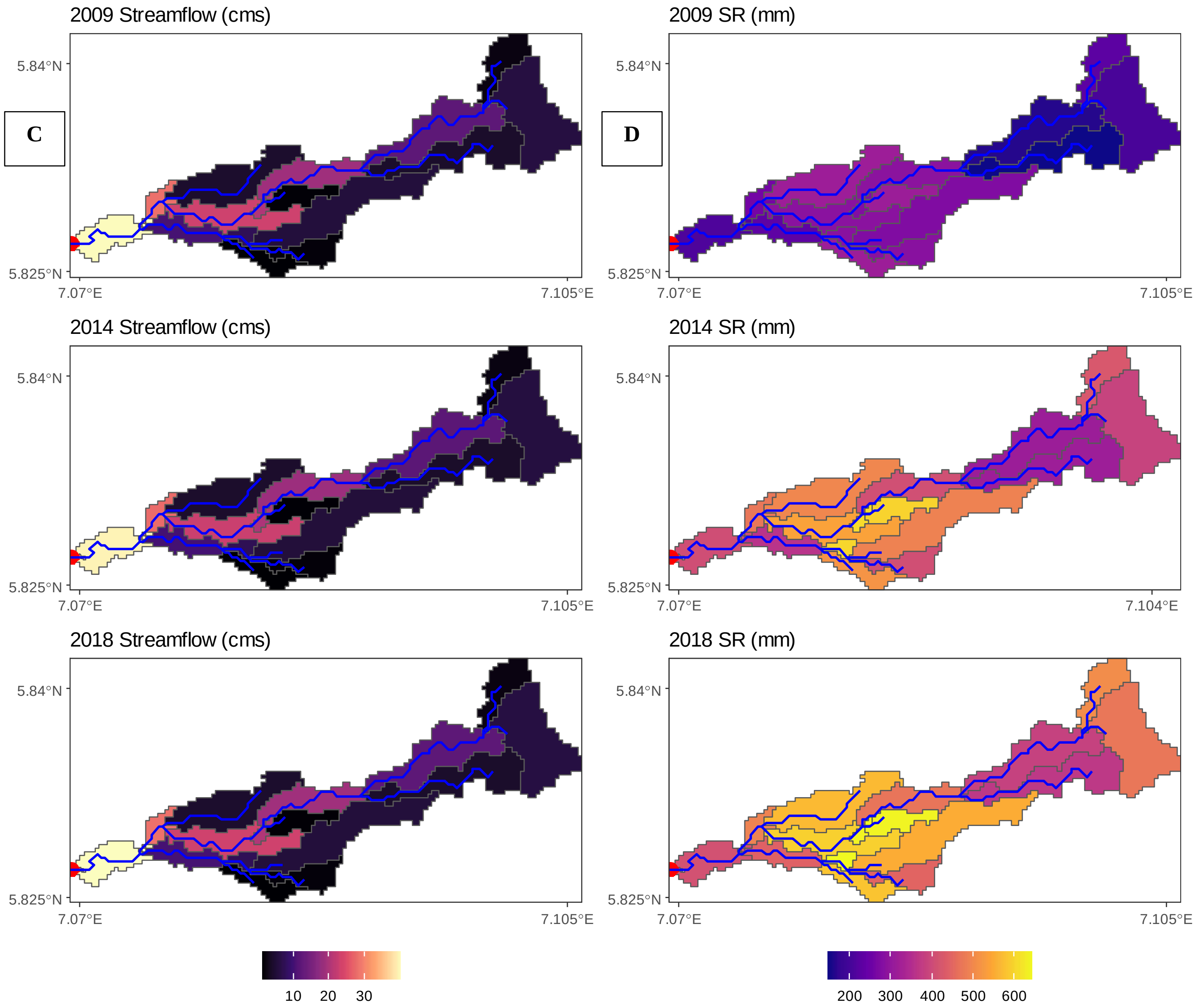
Appendix 5.4 cntd: A, IdeatoNorth1 gully watershed. Gully ID, 21. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 6 m^3/s in 2009 and 2018. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduction in all sub-basins between 2009 and 2018. F, Percolation. Reduction in percolation is observed across the sub-basins. G, evapotranspiration. 2009 had higher estimates than 2018. 2009 rainfall = 2447 mm and 2443 mm for 2018.



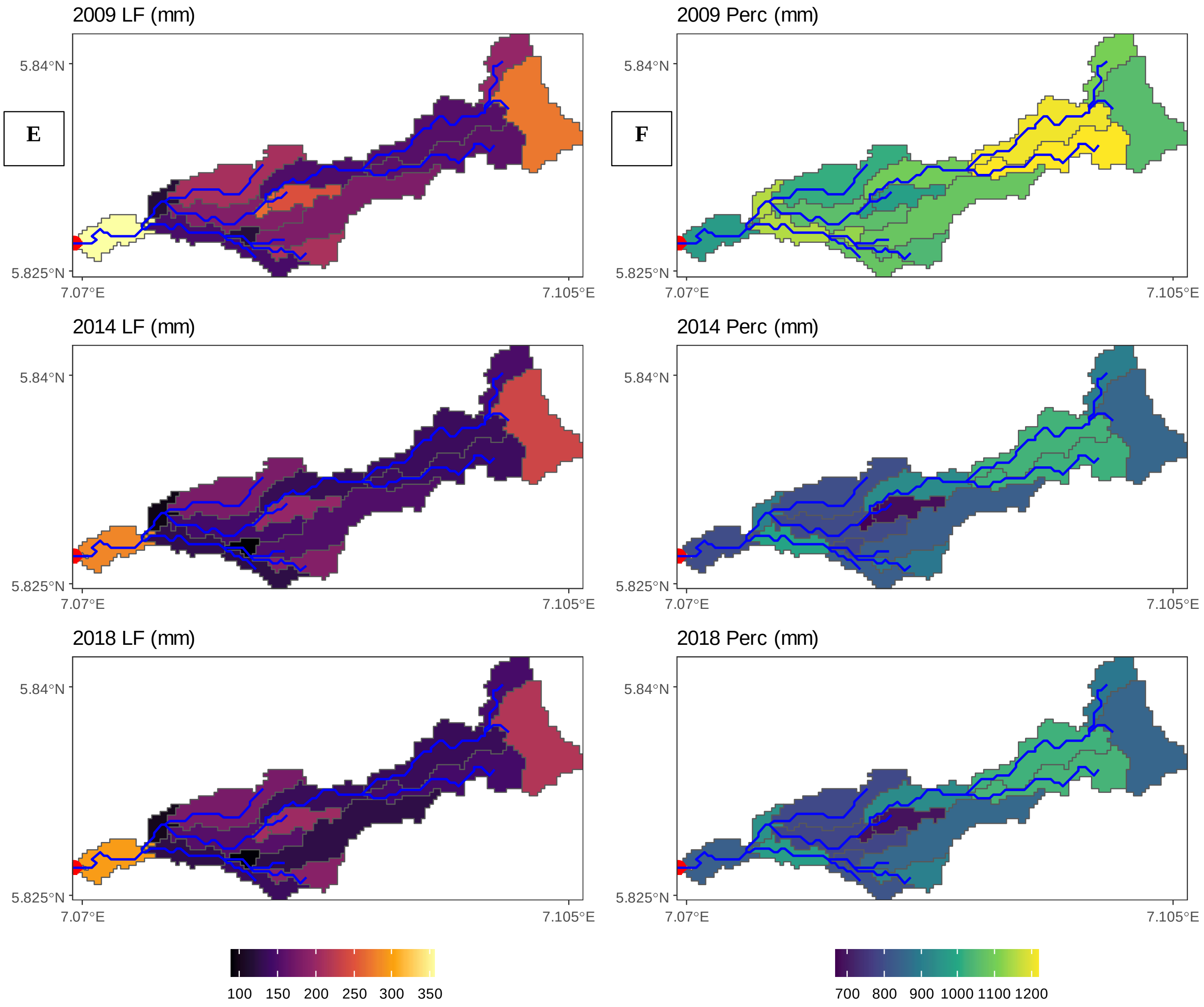
Appendix 5.5: IdeatoSouth3 gully watershed.



Appendix 5.5 cntd: IdeatoSouth3 gully watershed.

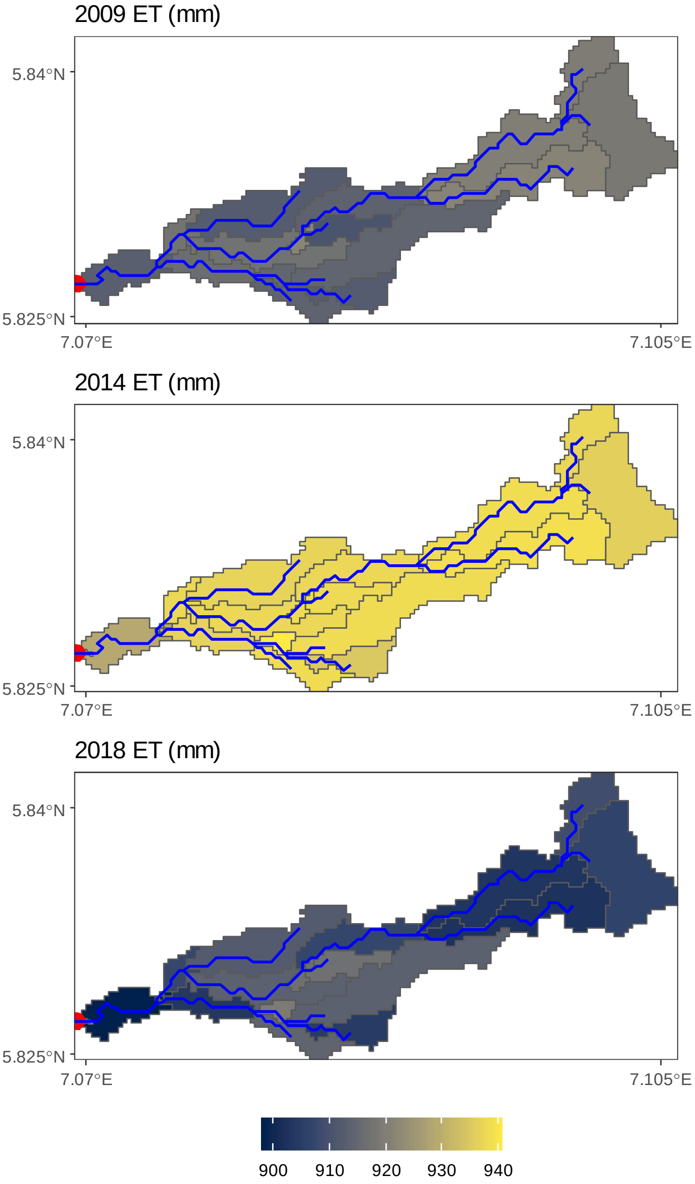


Appendix 5.5 cntd: IdeatoSouth3 gully watershed.

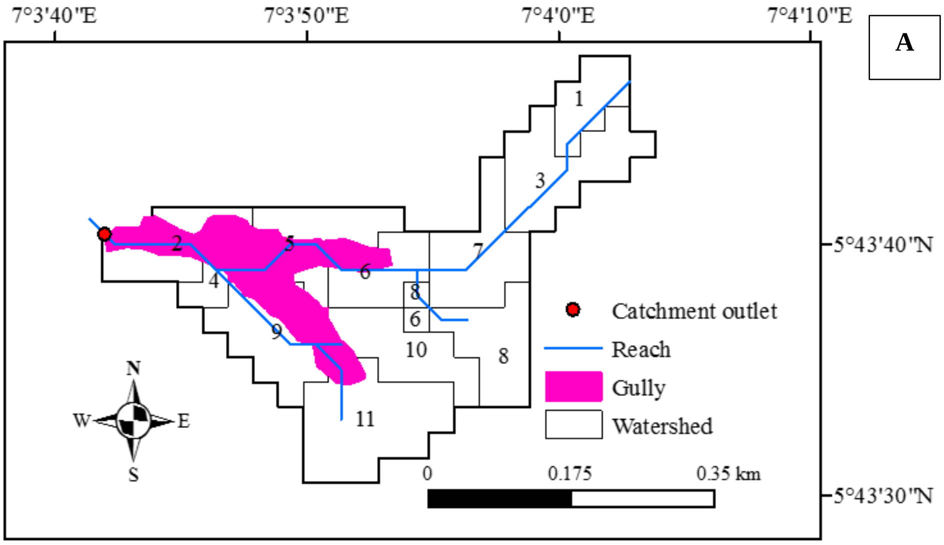


Appendix 5.5 cntd: IdeatoSouth3 gully watershed.

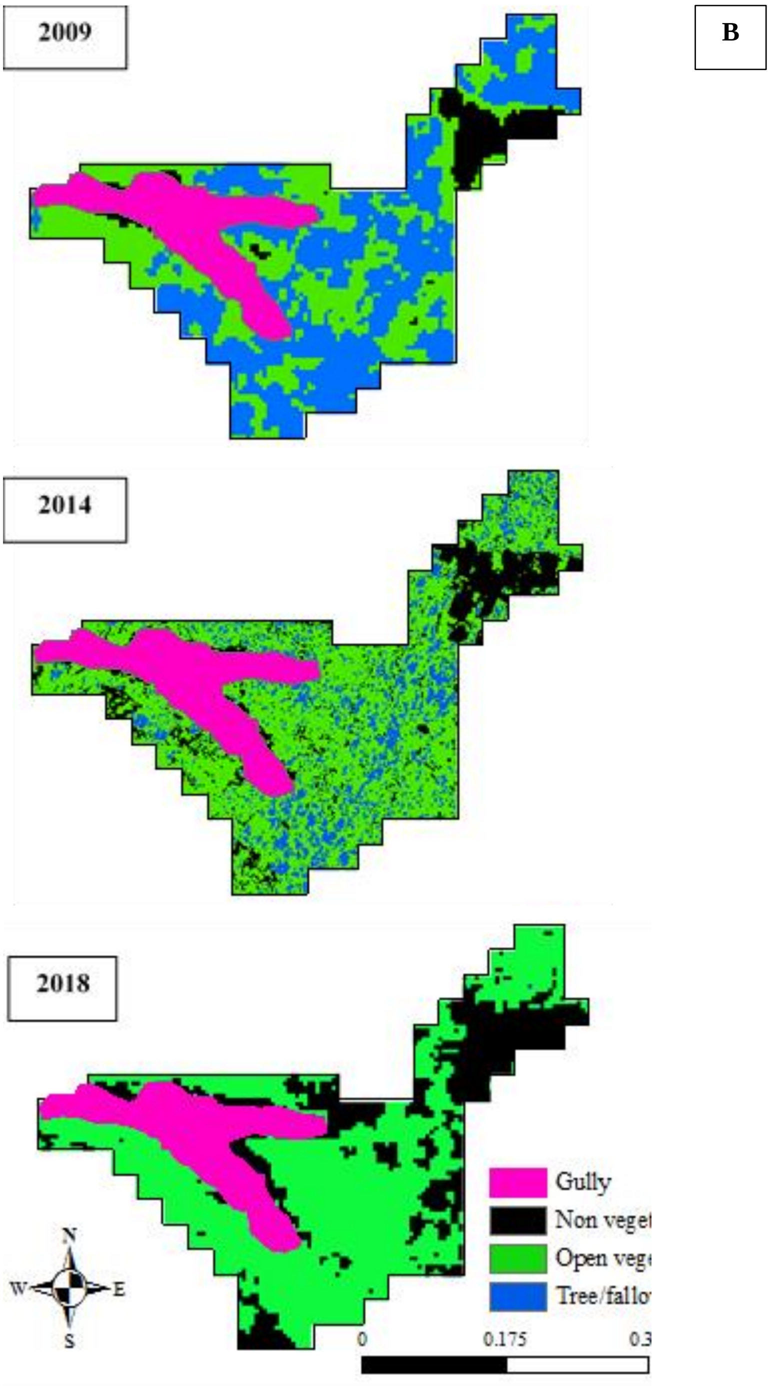
F



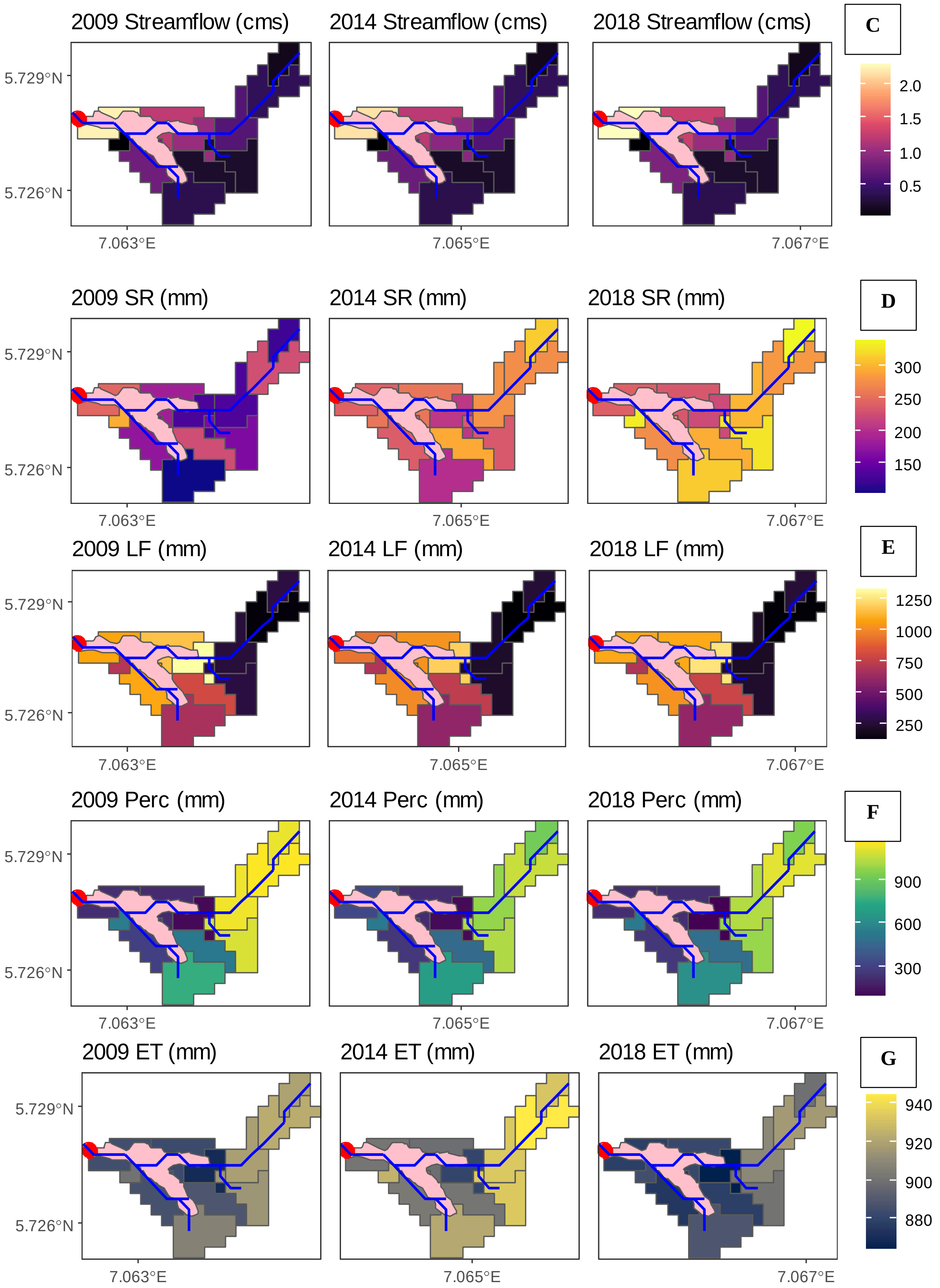
Appendix 5.5 cntd: A, IdeatoSouth3 gully watershed. Gully ID, 32. B, Land use change between 2009 and 2018 showing increased non-vegetated area. Non-vegetated area changed from low density to medium between 2009 and 204. C, streamflow estimates. Maximum streamflow was 1.5 m^3/s for all years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing increased flow between 2014 and 2018 in 10 sub-basins including sub-basin 12 between 2014 and 2018. F, Percolation. There was higher percolation in sub-basin 12. G, evapotranspiration. 2014 had higher estimates. 2009 rainfall = 2447 mm, 2412 mm in 2014 and 2443 mm for 2018.



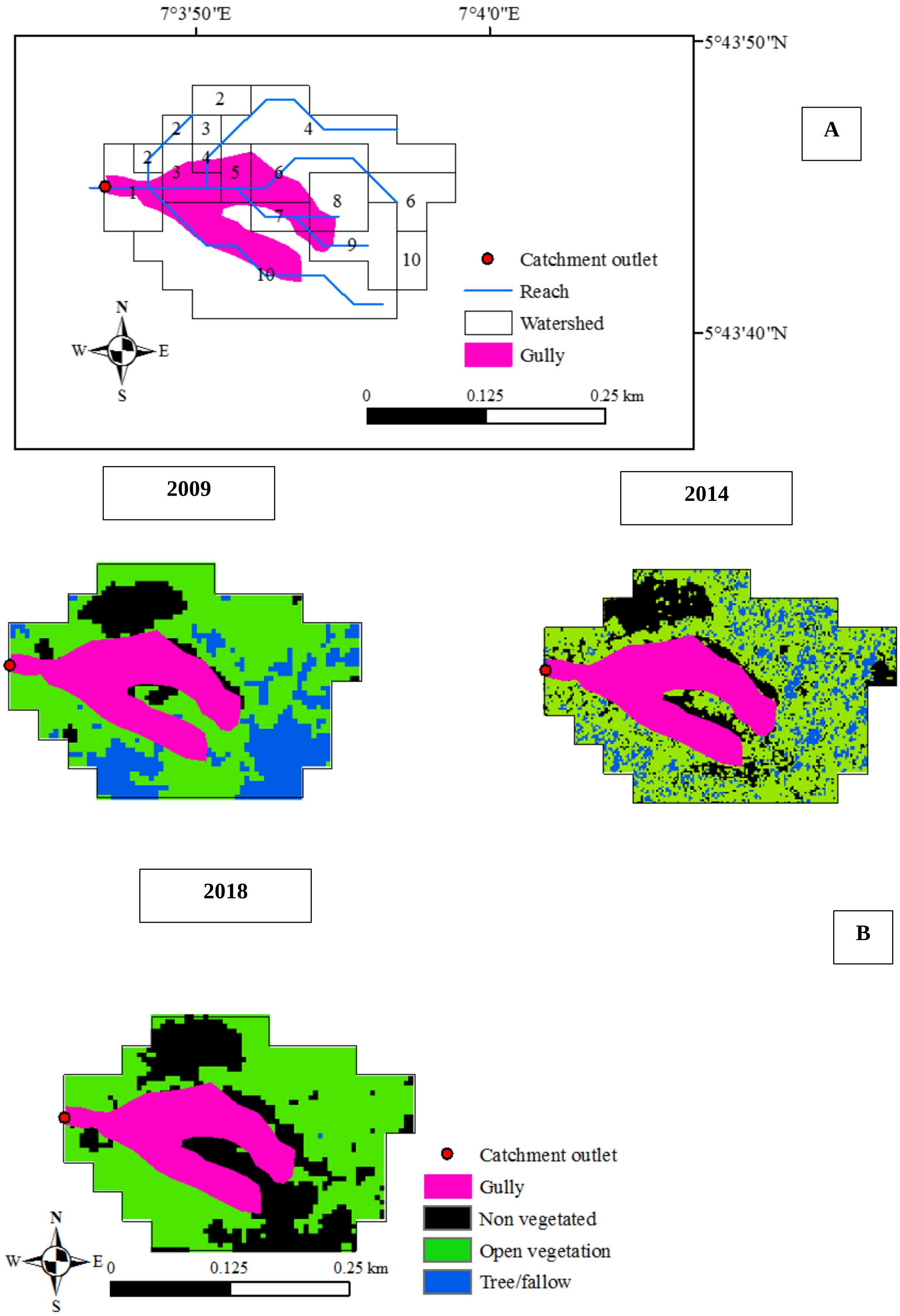
Appendix 5.6: Isu_gully1 gully watershed.



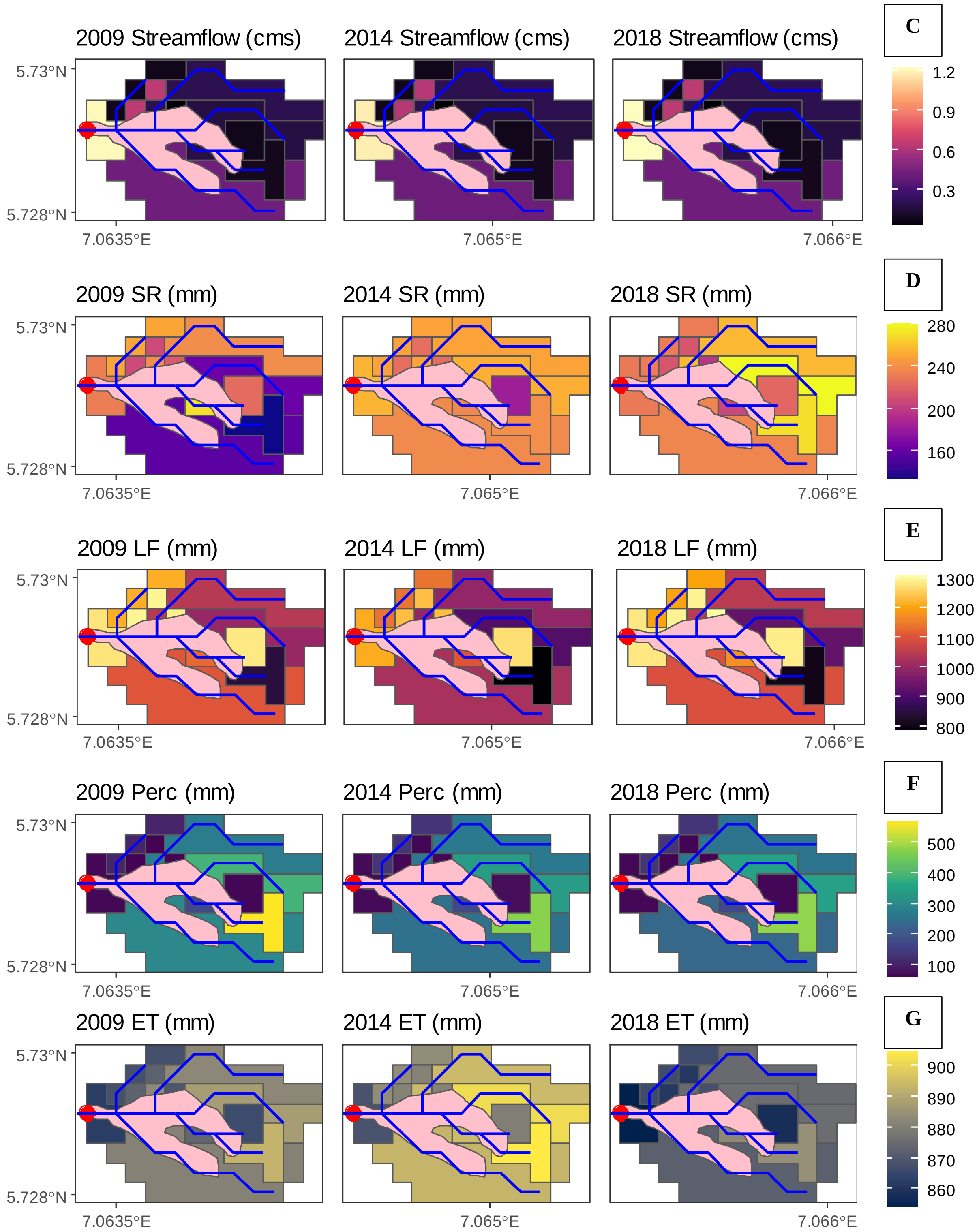
Appendix 5.6 cntd: Isu_gully1 gully watershed.



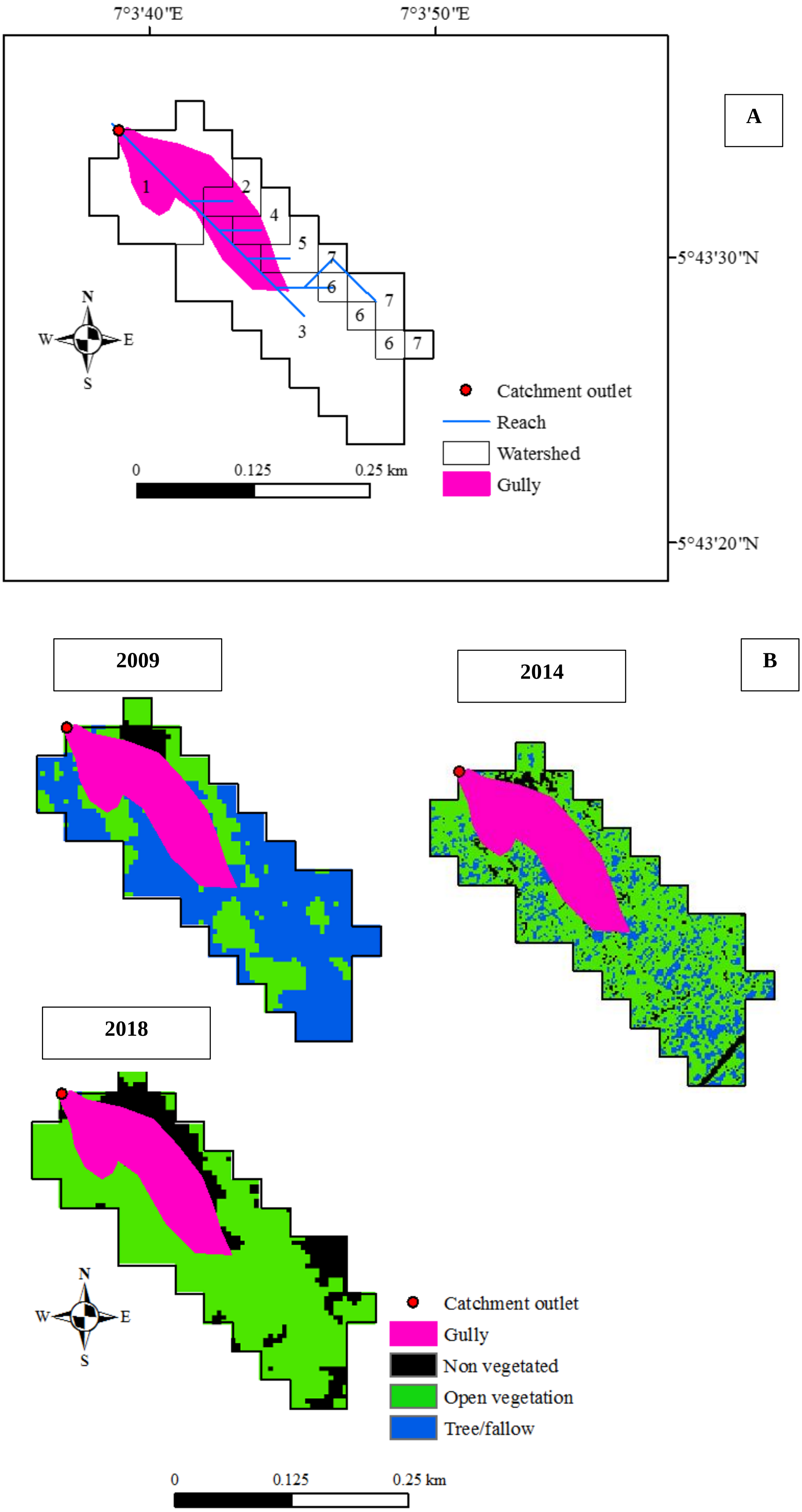
Appendix 5.6 cntd: A, Isu_gully1 watershed. Gully ID, 8. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Highest maximum streamflow was 2.3 m^3/s in 2018 while 2009 and 2014 were 2.2 m^3/s. D, surface runoff contribution to streamflow showing increased runoff in all but two sub-basins (2 and 4) between 2009 and 2014. E, lateral flow showing increased in modelled lateral flow in sub-basins 2, 5 and 6 between 2009 and 2014. F, Percolation. There was higher percolation in sub-basins 2, 5 and 6 between 2009 and 2014. G, evapotranspiration. 2014 had higher estimates. 2009 rainfall = 2447 mm, 2412 mm in 2014 and 2443 mm for 2018.



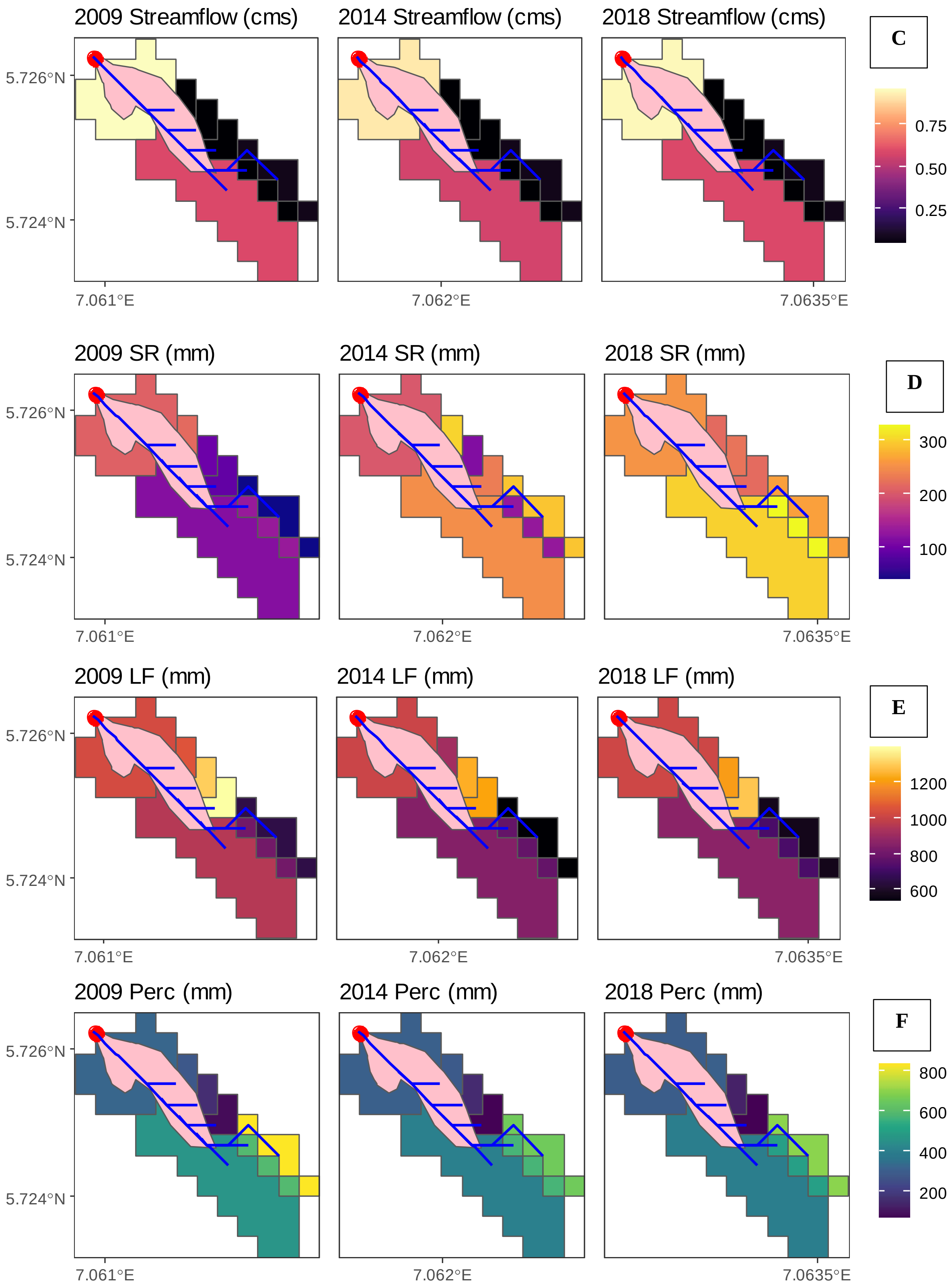
Appendix 5.7: Isu_gully2 gully watershed.



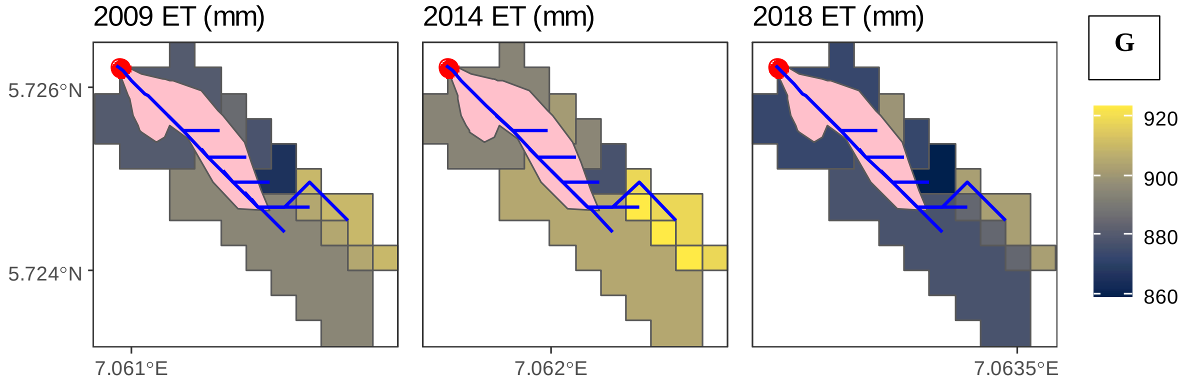
Appendix 5.7 cntd: A, Isu_gully2 watershed. Gully ID, 9. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 0.4 m^3/s for all years. D, surface runoff contribution to streamflow showing increased runoff in all but three sub-basins (2, 7, 8) between 2009 and 2014. E, lateral flow showing reduced flow in all sub-basins between 2009 and 2014. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2014 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm, 2412 mm in 2014 and 2443 mm for 2018.



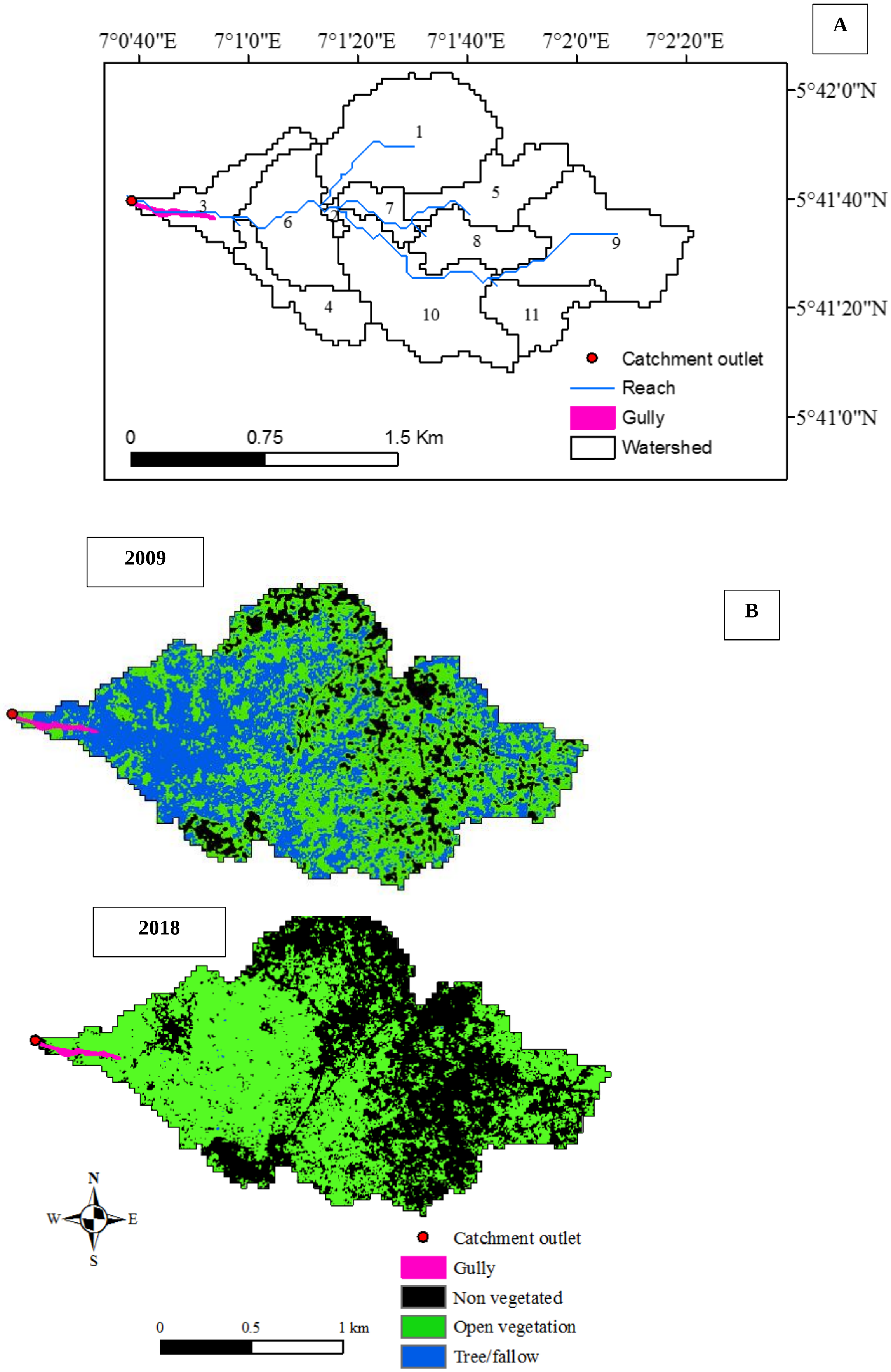
Appendix 5.8: Isu_gully3 gully watershed.



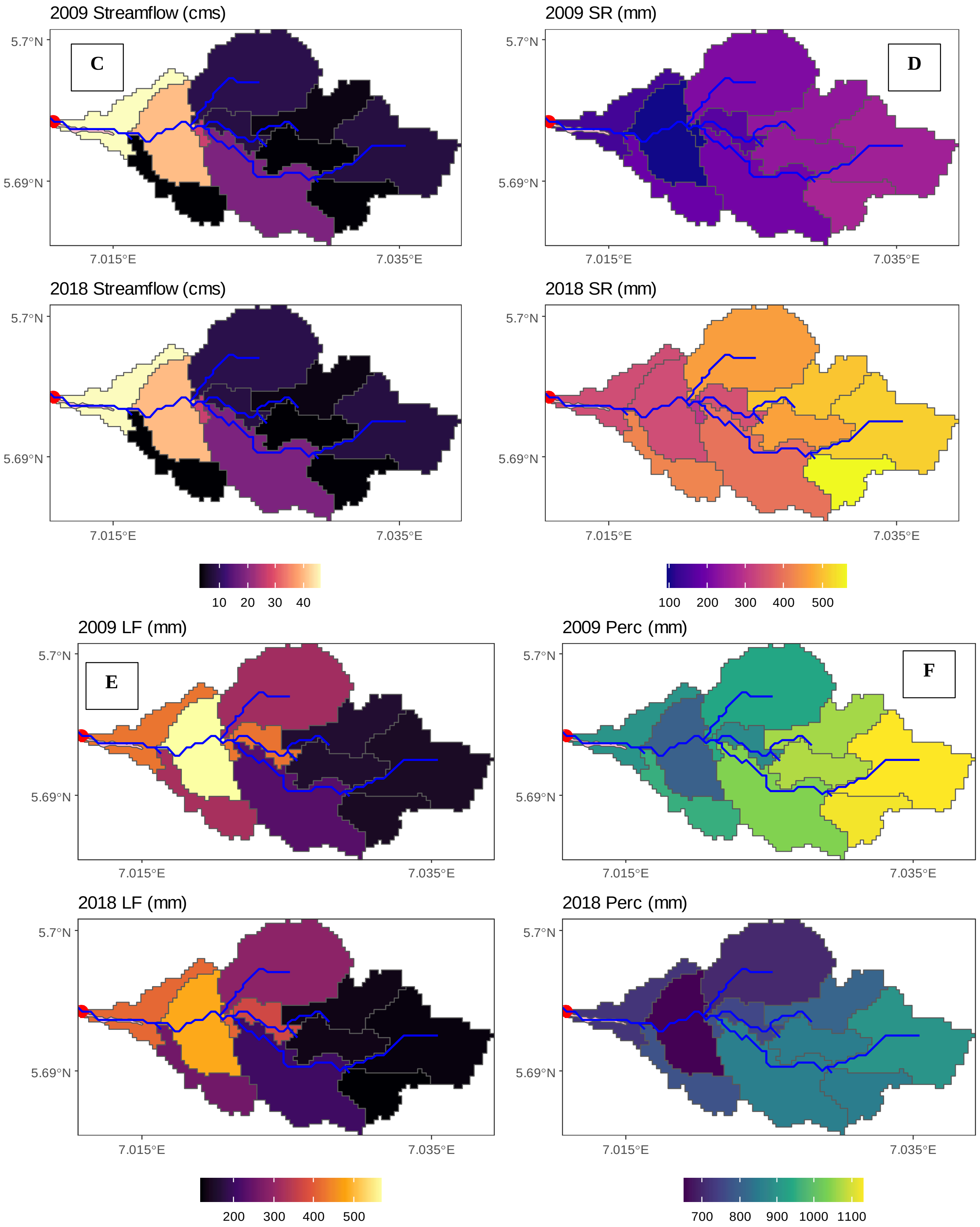
Appendix 5.8 cntd: Isu_gully3 gully watershed.



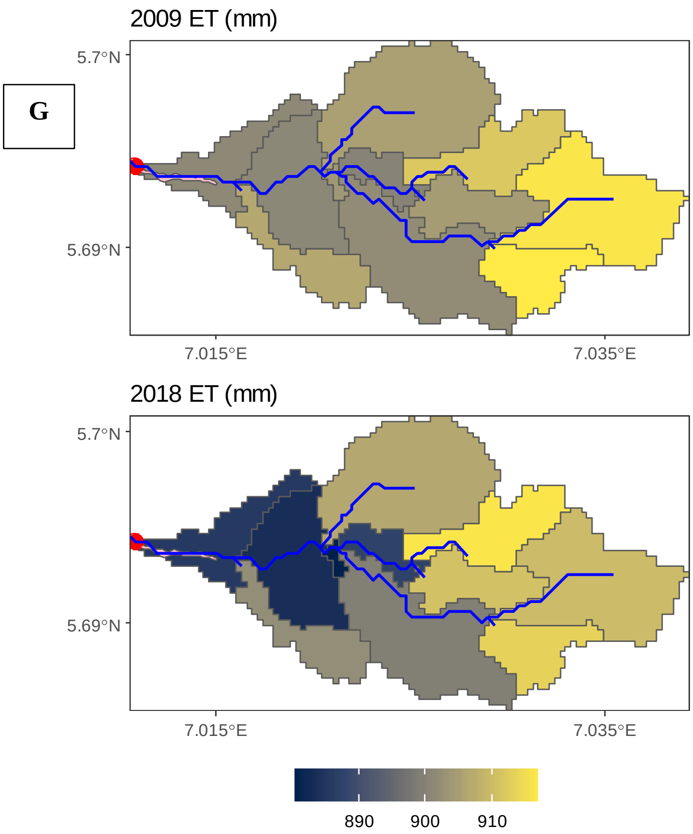
Appendix 5.8 cntd: A, Isu_gully3 watershed. Gully ID, 9. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 1 m^3/s for all years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduced flow in all sub-basins between 2009 and 2014. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2014 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm, 2412 mm in 2014 and 2443 mm for 2018.



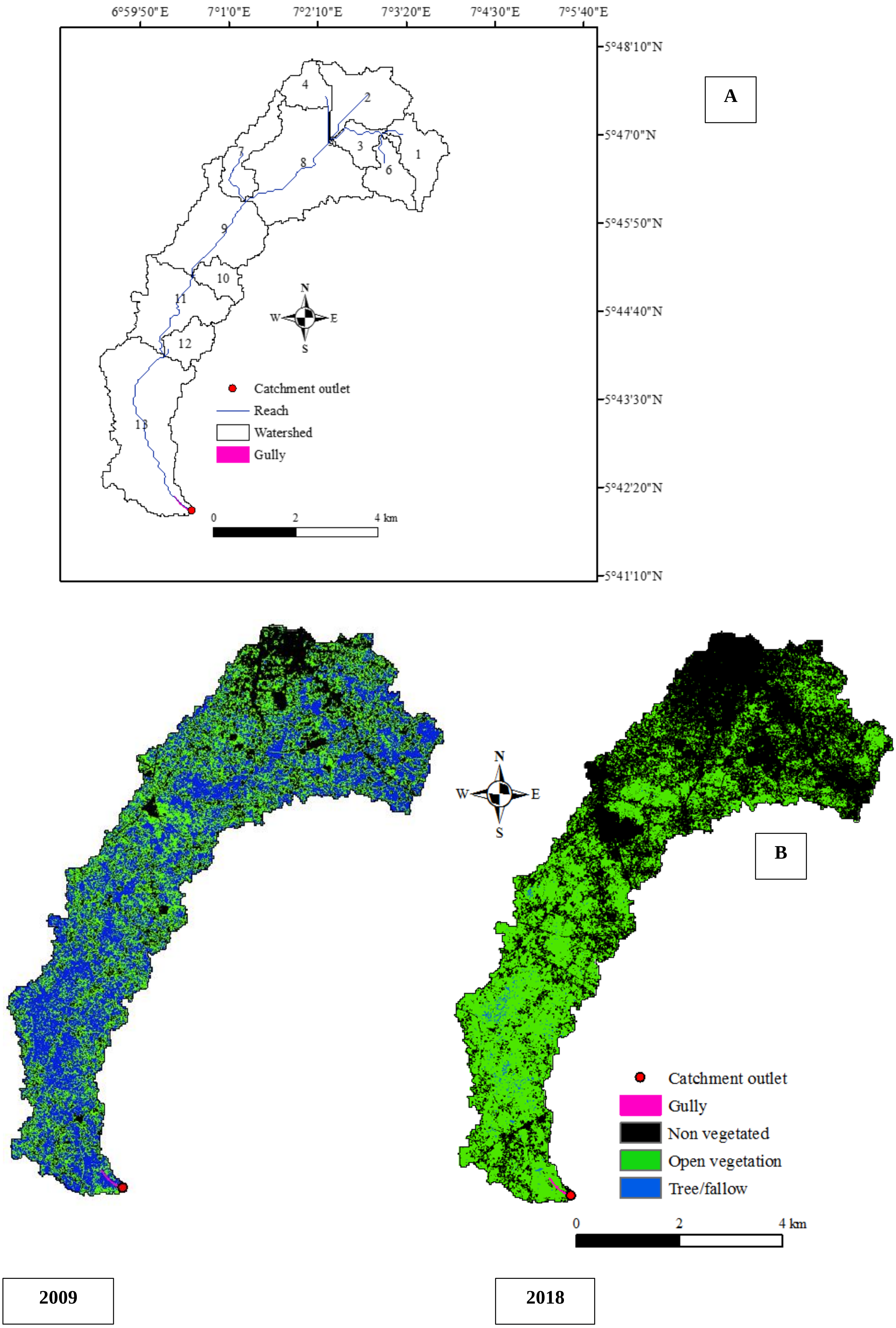
Appendix 5.9: Njaba4 gully watershed.



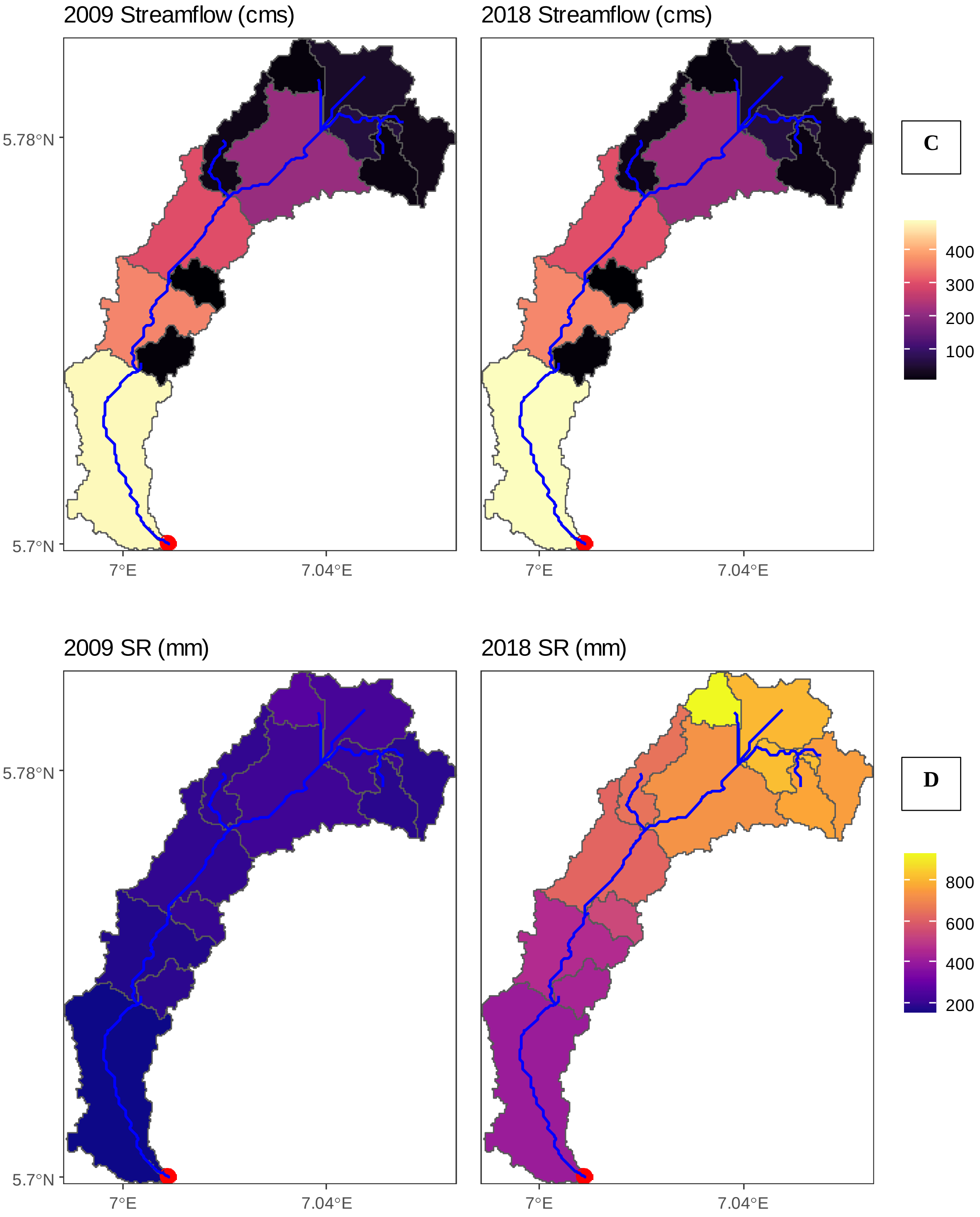
Appendix 5.9 cntd: Njaba4 gully watershed.



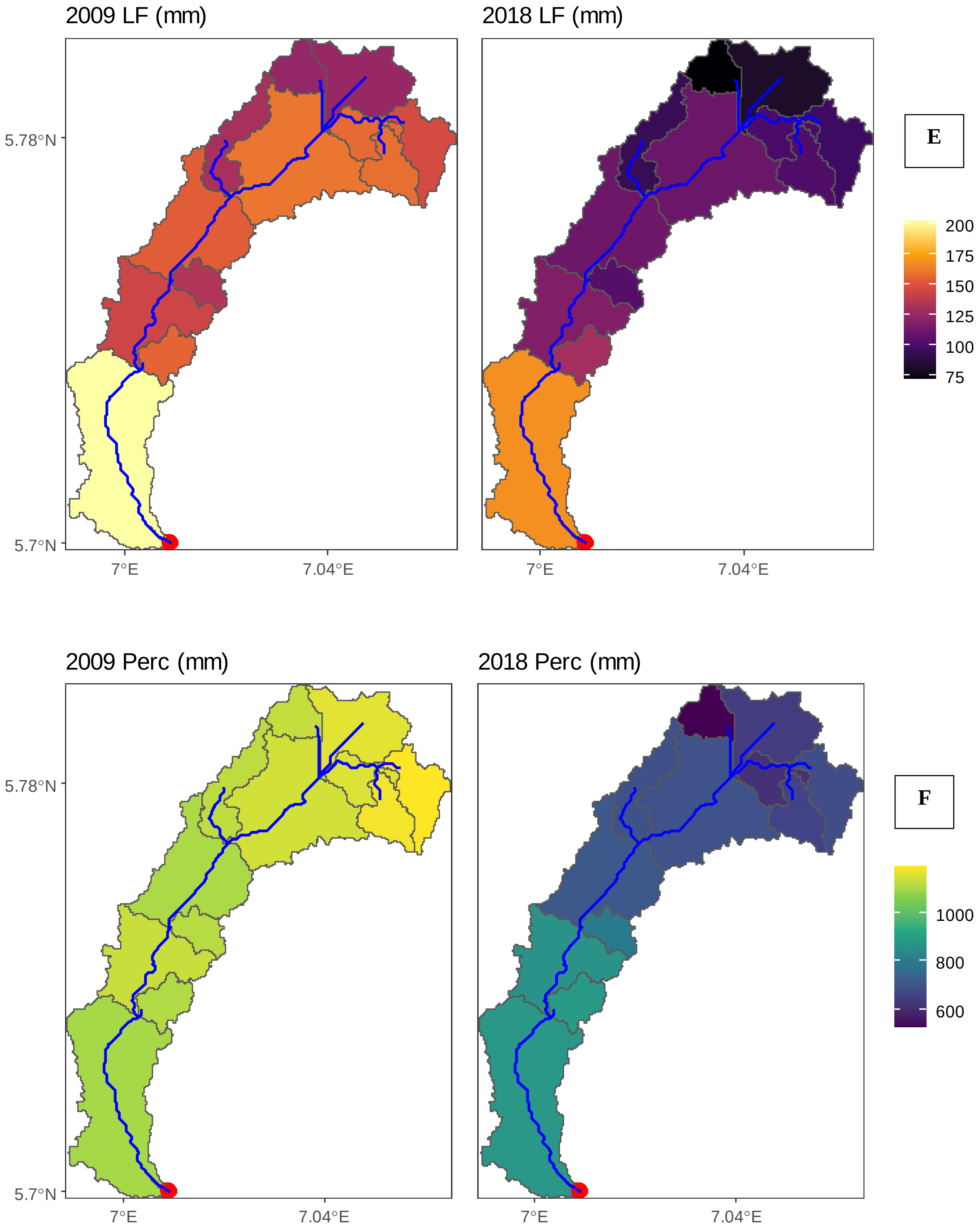
Appendix 5.9 cntd: A, Njaba4 gully watershed. Gully ID, 2. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area changed from low to medium density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 3 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduced flow in all sub-basins. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2362 mm and 2351 mm for 2018.



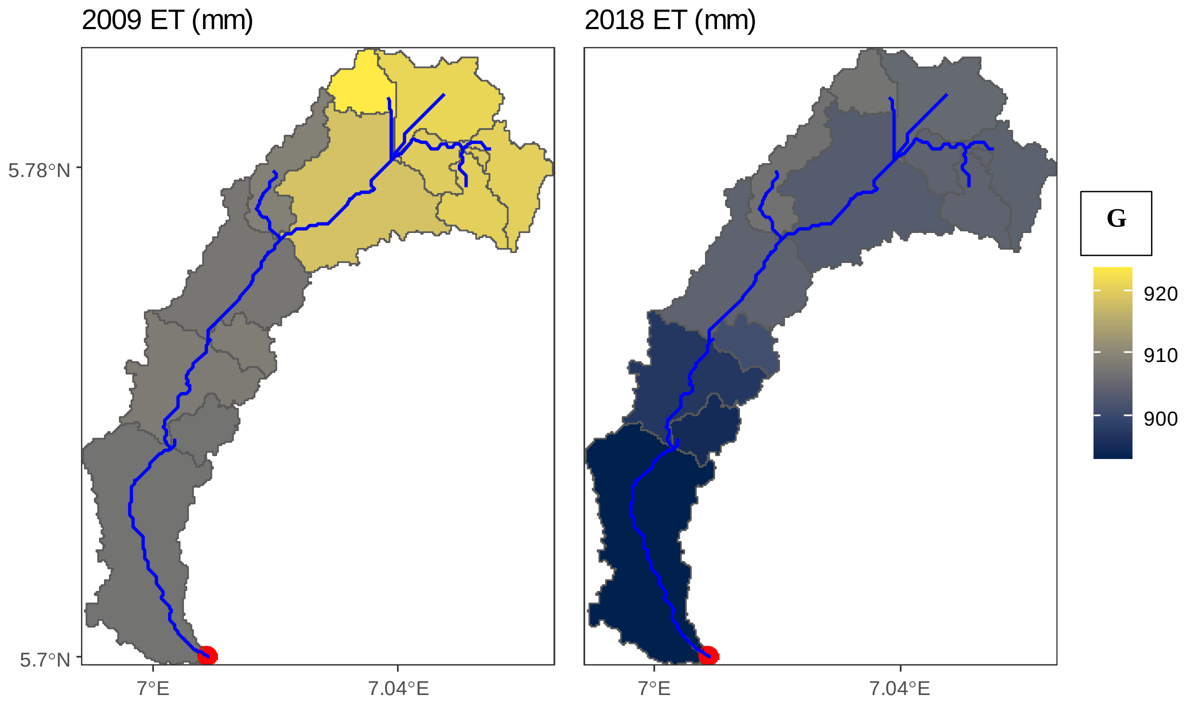
Appendix 5.10: Njaba5 gully watershed.



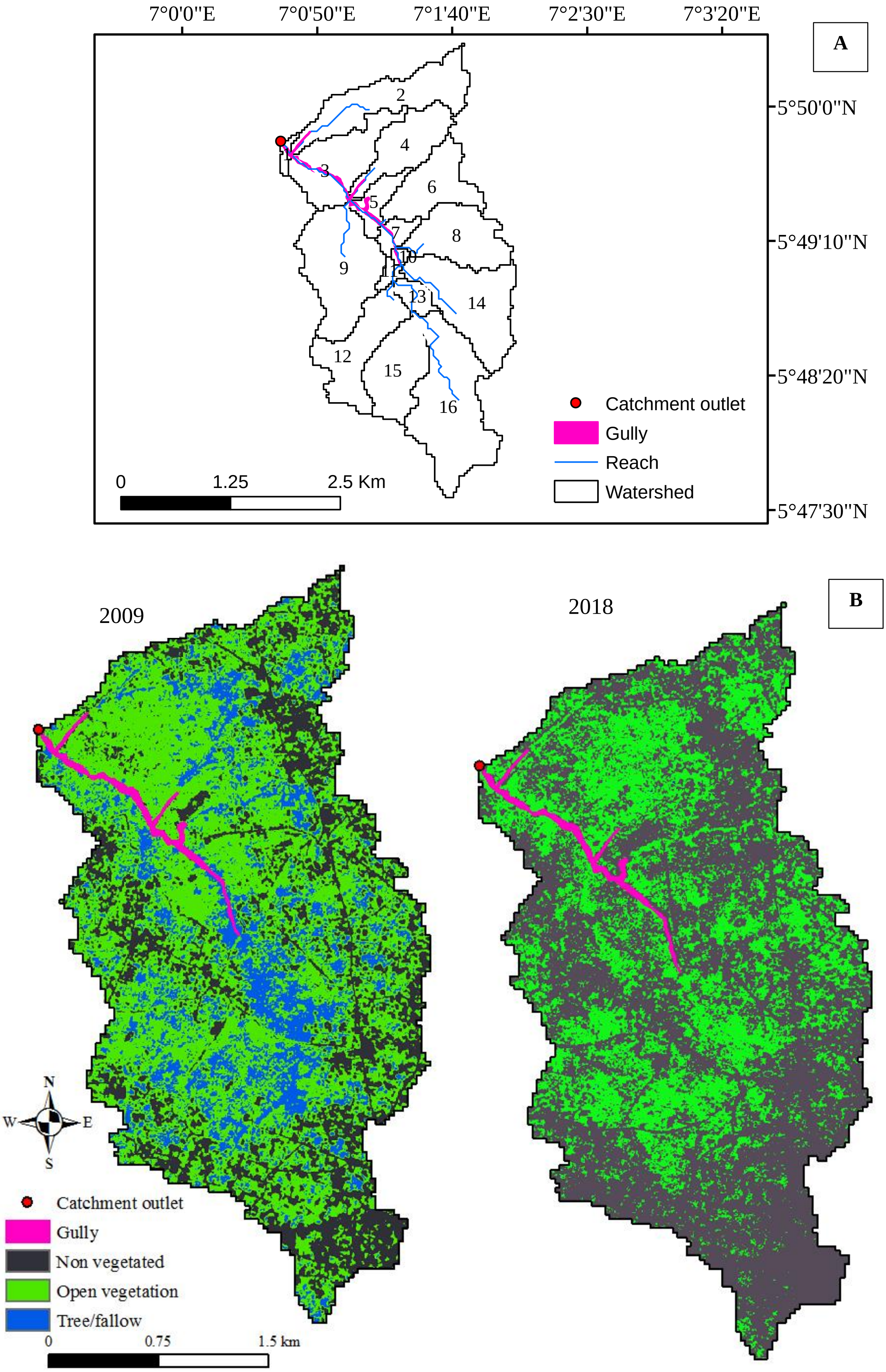
Appendix 5.10 cntd: Njaba5 gully watershed.



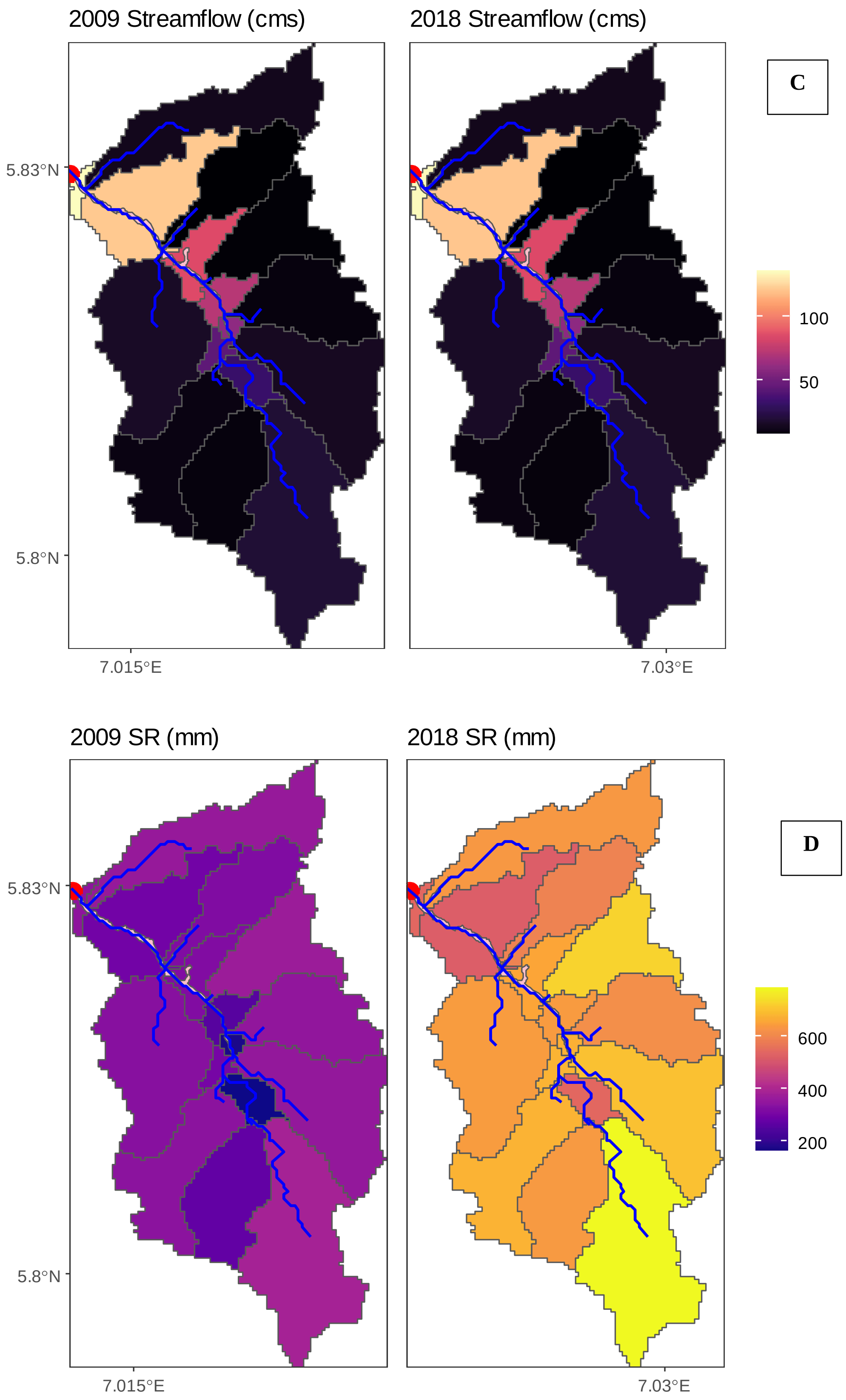
Appendix 5.10 cntd: Njaba5 gully watershed.



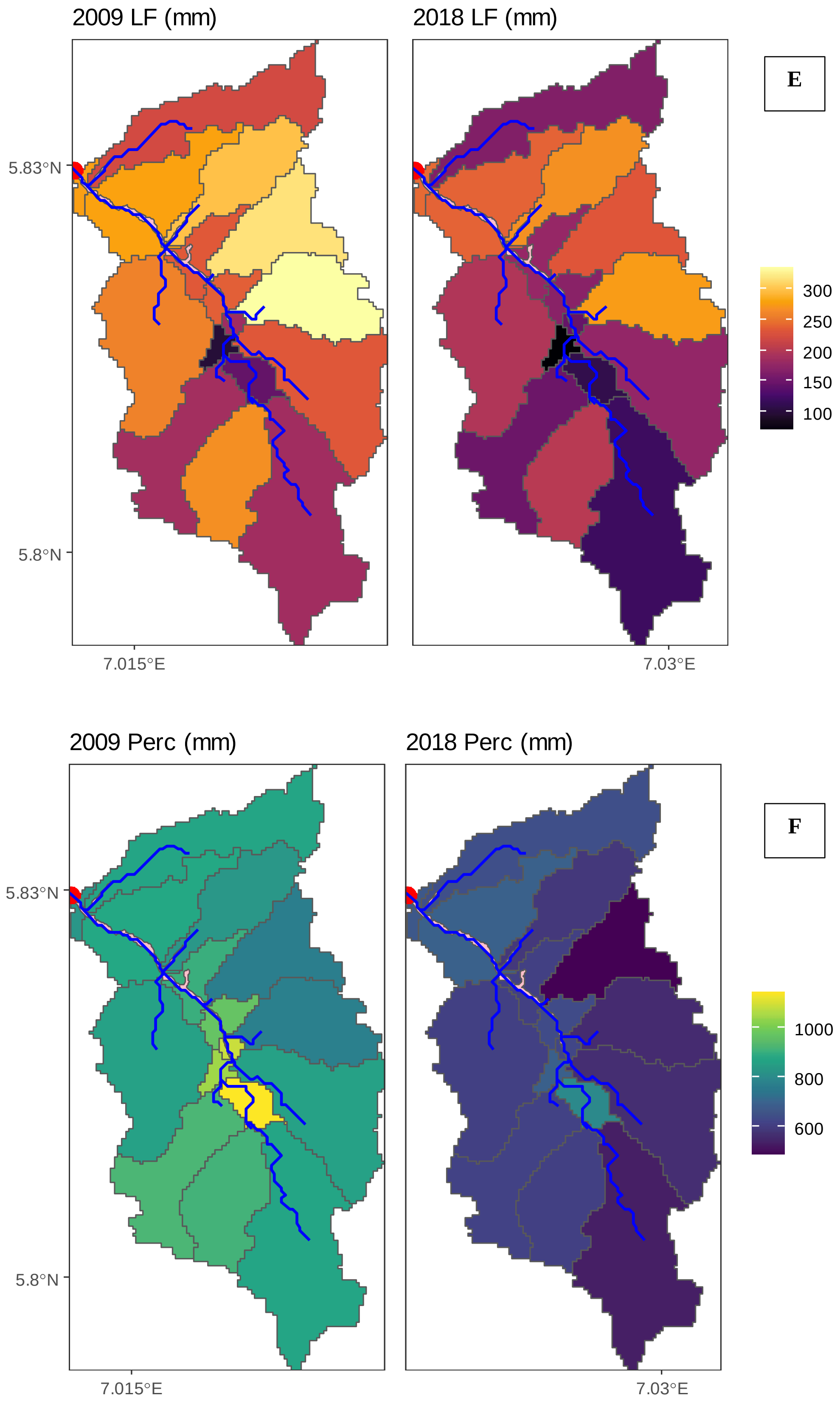
Appendix 5.10 cntd: A, Njaba5 gully watershed. Gully ID, 33. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area changed from low to high density between 2009 and 2018. C, streamflow estimates. Maximum streamflow changed from 482 to 487 m^3/s between 2009 and 2018. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduced flow in all sub-basins. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2362 mm and 2351 mm for 2018.



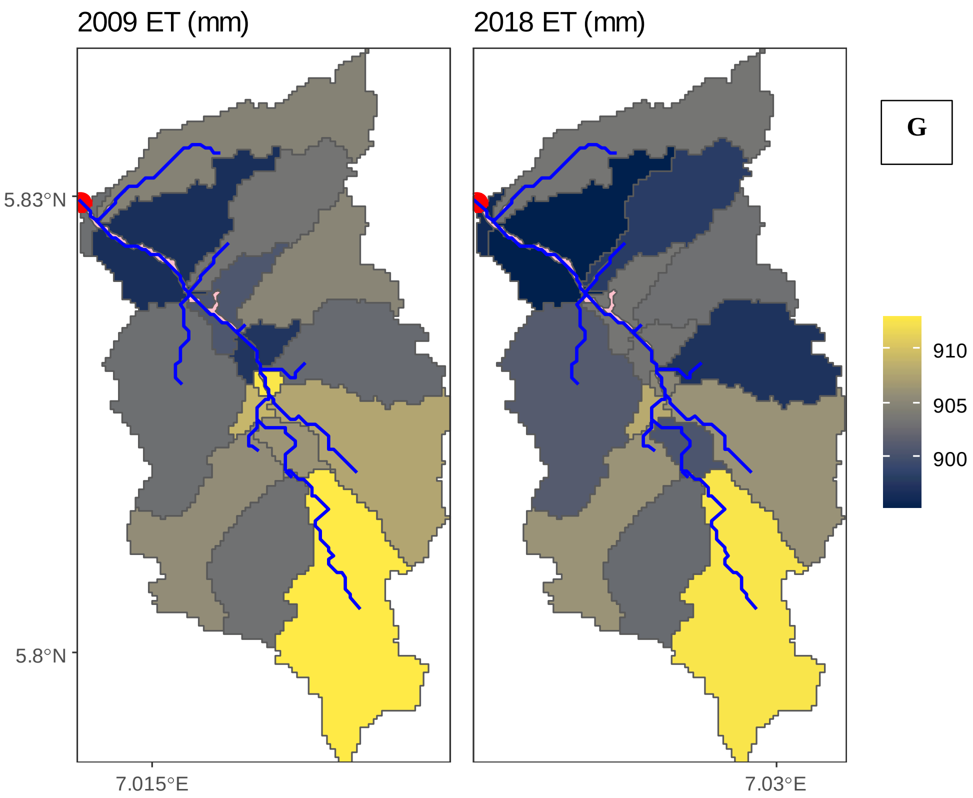
Appendix 5.11: Orlu1 gully watershed.



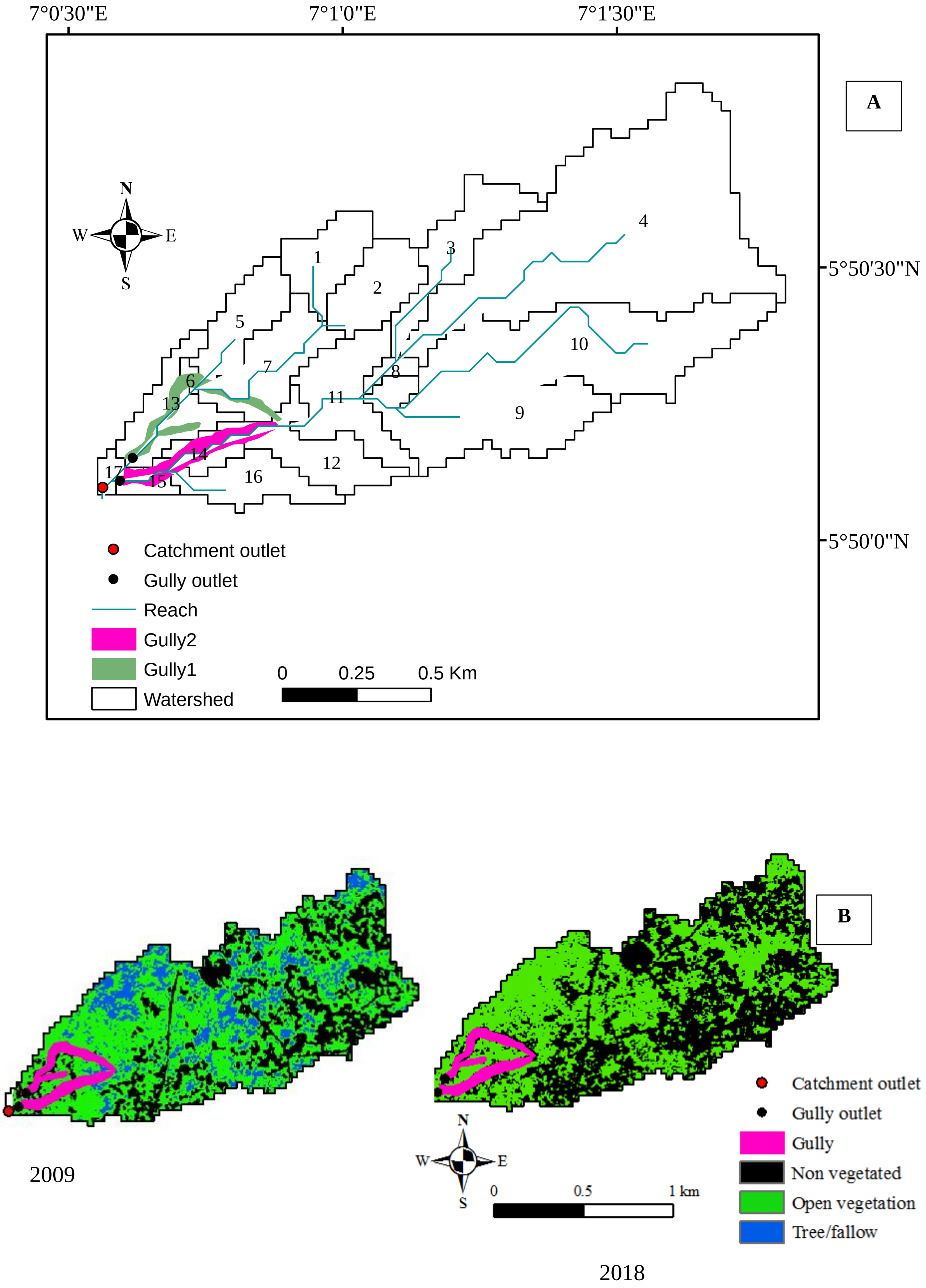
Appendix 5.11 cntd: Orlu1 gully watershed.



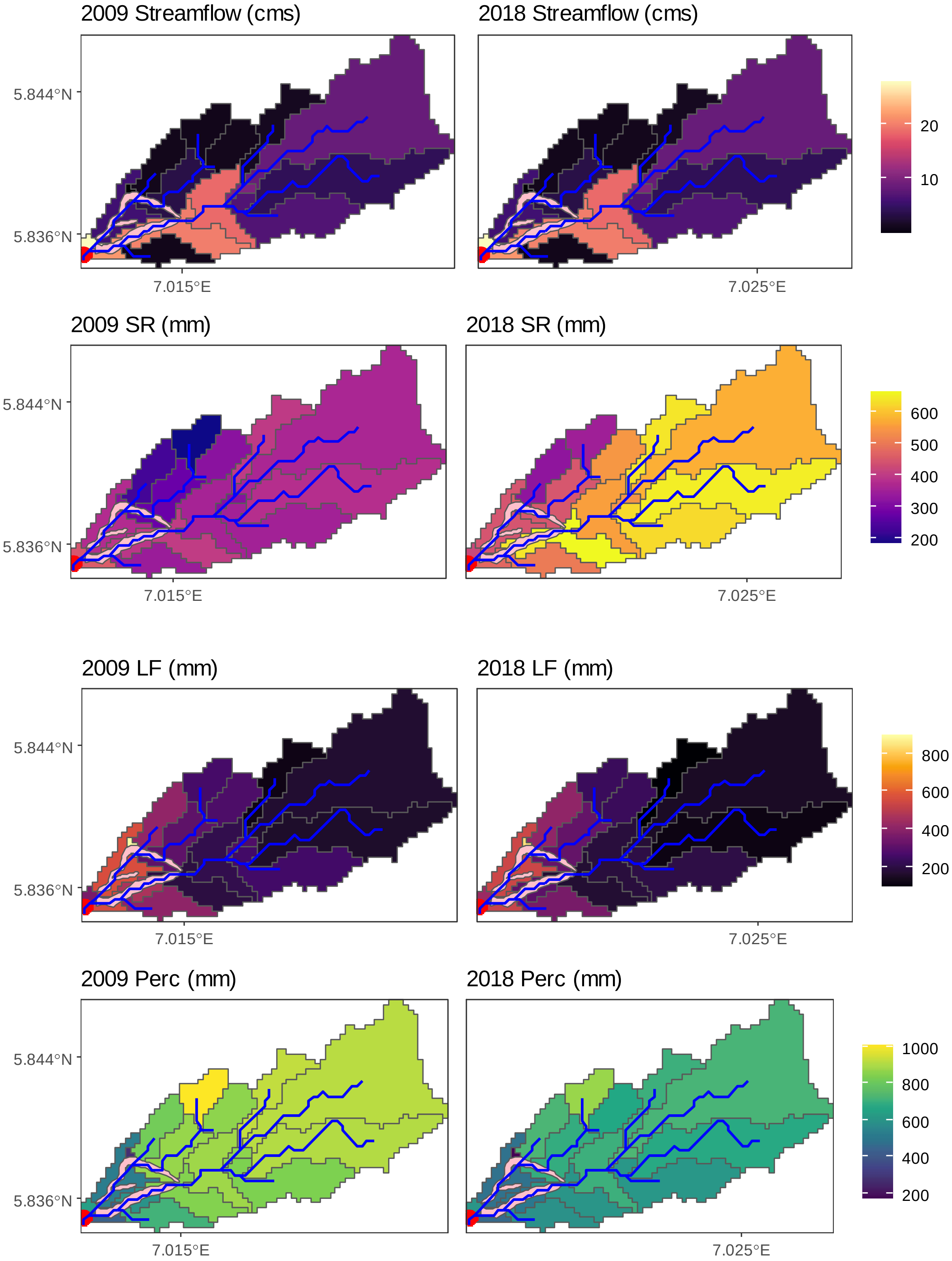
Appendix 5.11 cntd: Orlu1 gully watershed.



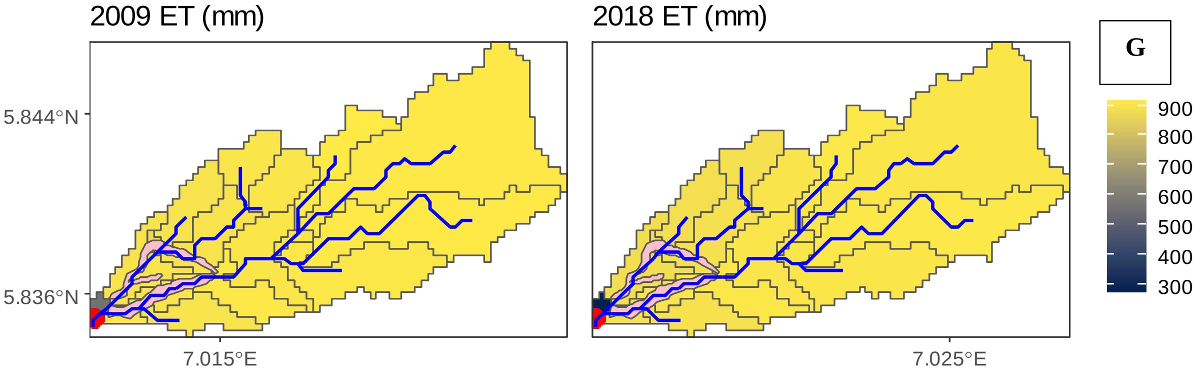
Appendix 5.11 cntd: A, Orlu1 gully watershed. Gully ID, 12. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area changed from medium to high density between 2009 and 2018. The Orlu1 catchment is the most urbanised catchment in the study area. C, streamflow estimates. Maximum streamflow dropped from 137 to 136 m^3/s between 2009 and 2018. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduced flow in all sub-basins. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2362 mm and 2351 mm for 2018.



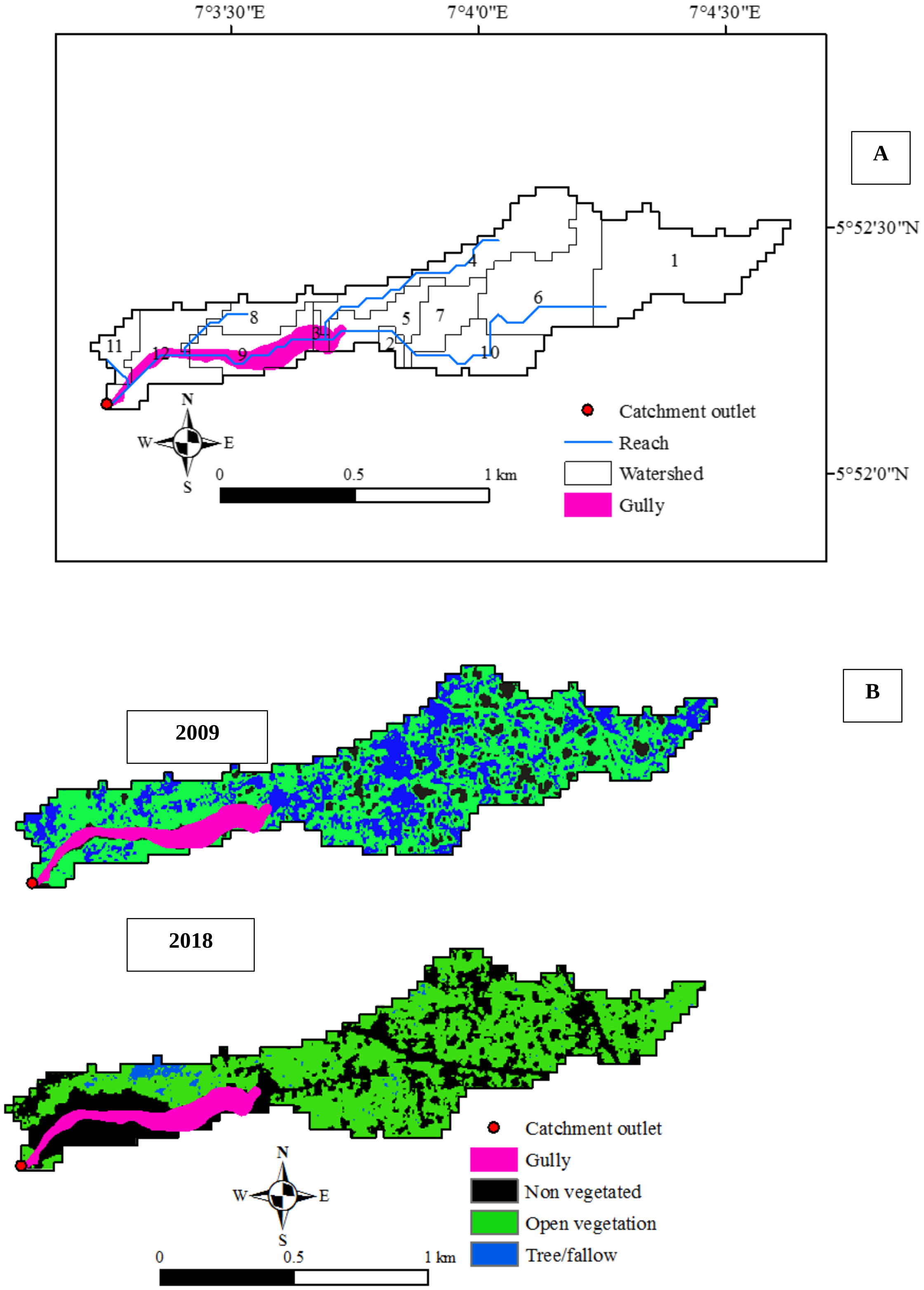
Appendix 5.12 cntd: Orlu2 gully watershed.



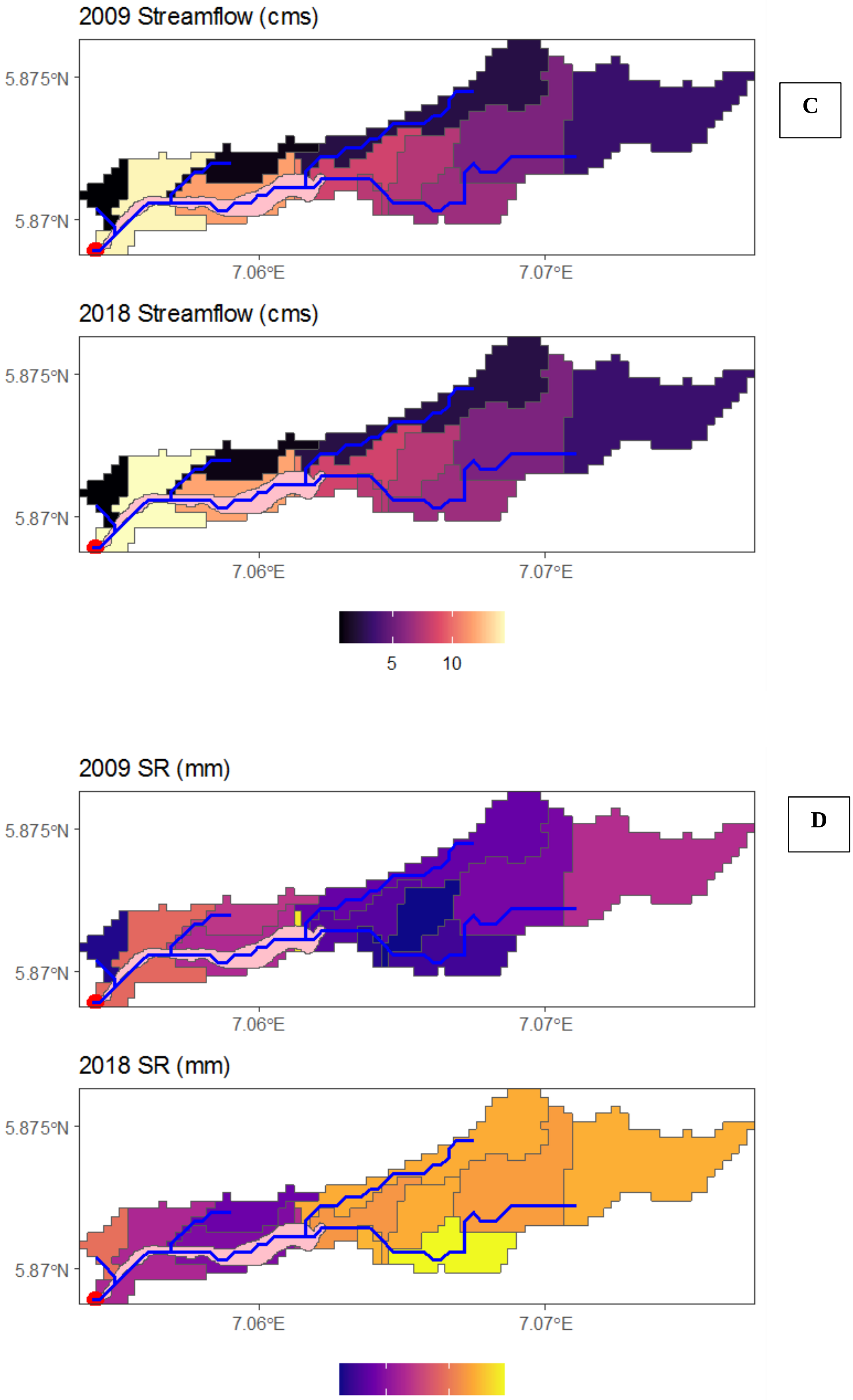
Appendix 5.12 cntd: Orlu2 gully watershed.



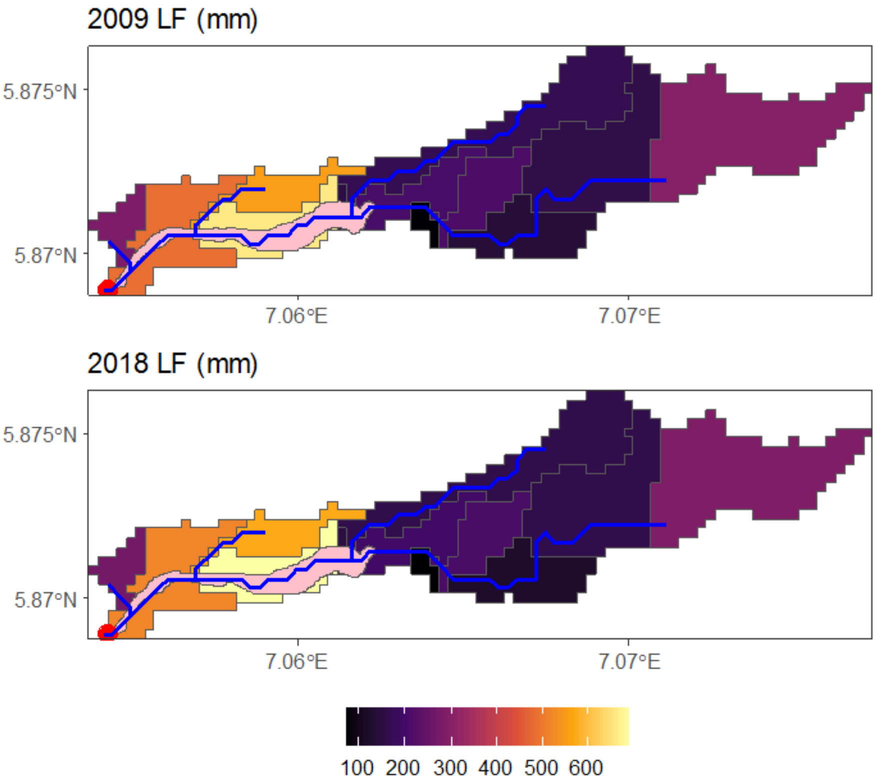
Appendix 5.12 cntd: A, Orlu2 gully watershed. Gully ID, 12. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area changed from medium to high density between 2009 and 2018. C, streamflow estimates. Maximum streamflow was 28 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow showing reduced flow in all sub-basins. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2369 mm and 2363 mm for 2018.



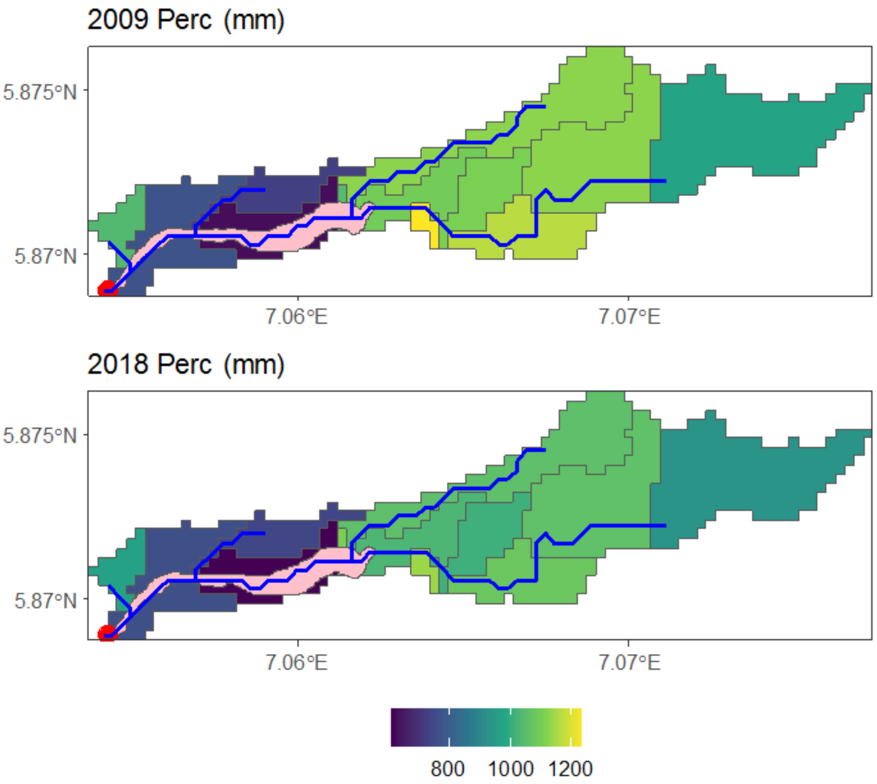
Appendix 5.13: Urualla_gully1 gully watershed.



Appendix 5.13 cntd: Urualla_gully1 gully watershed.

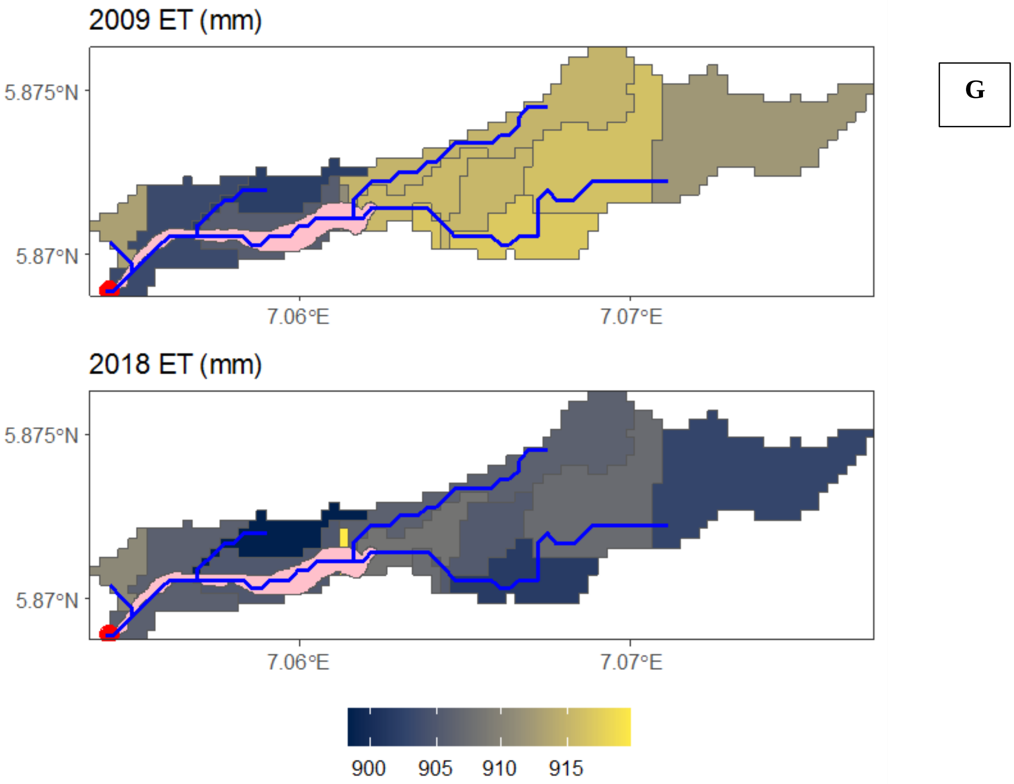


E

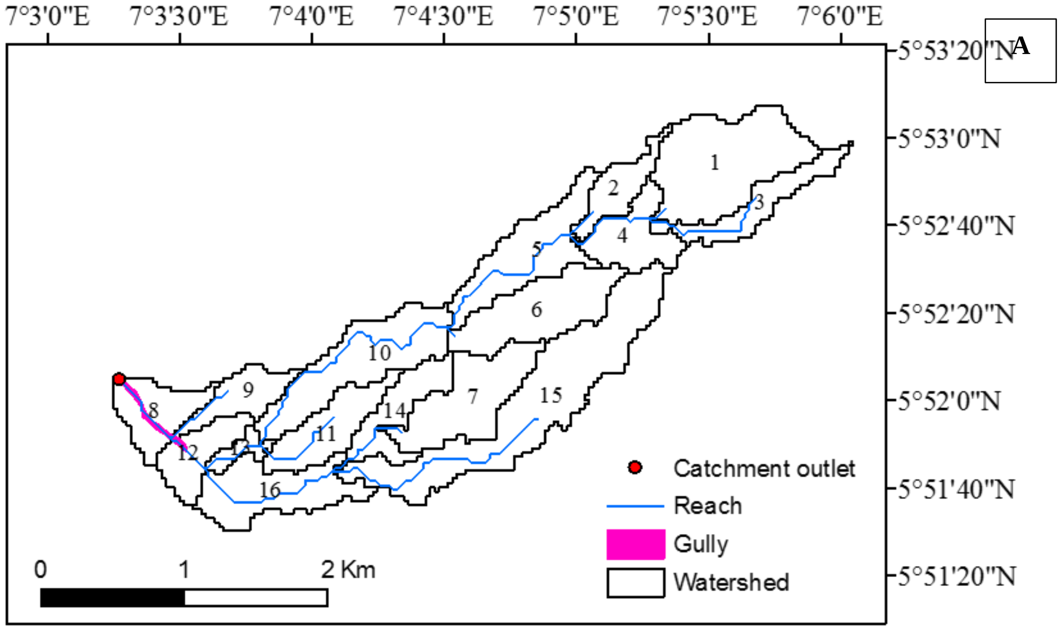


F

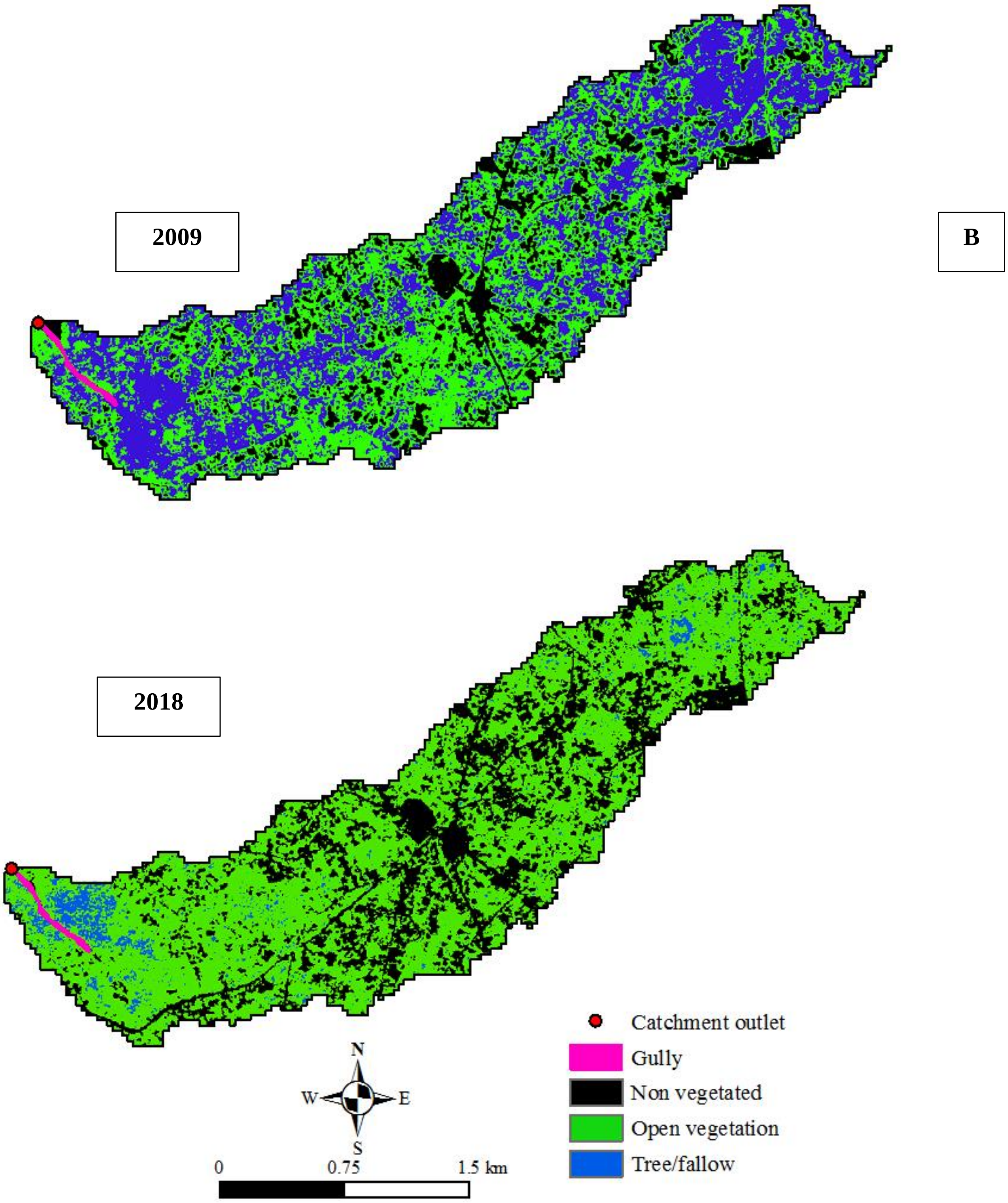
Appendix 5.13 cntd: Urualla_gully1 gully watershed.



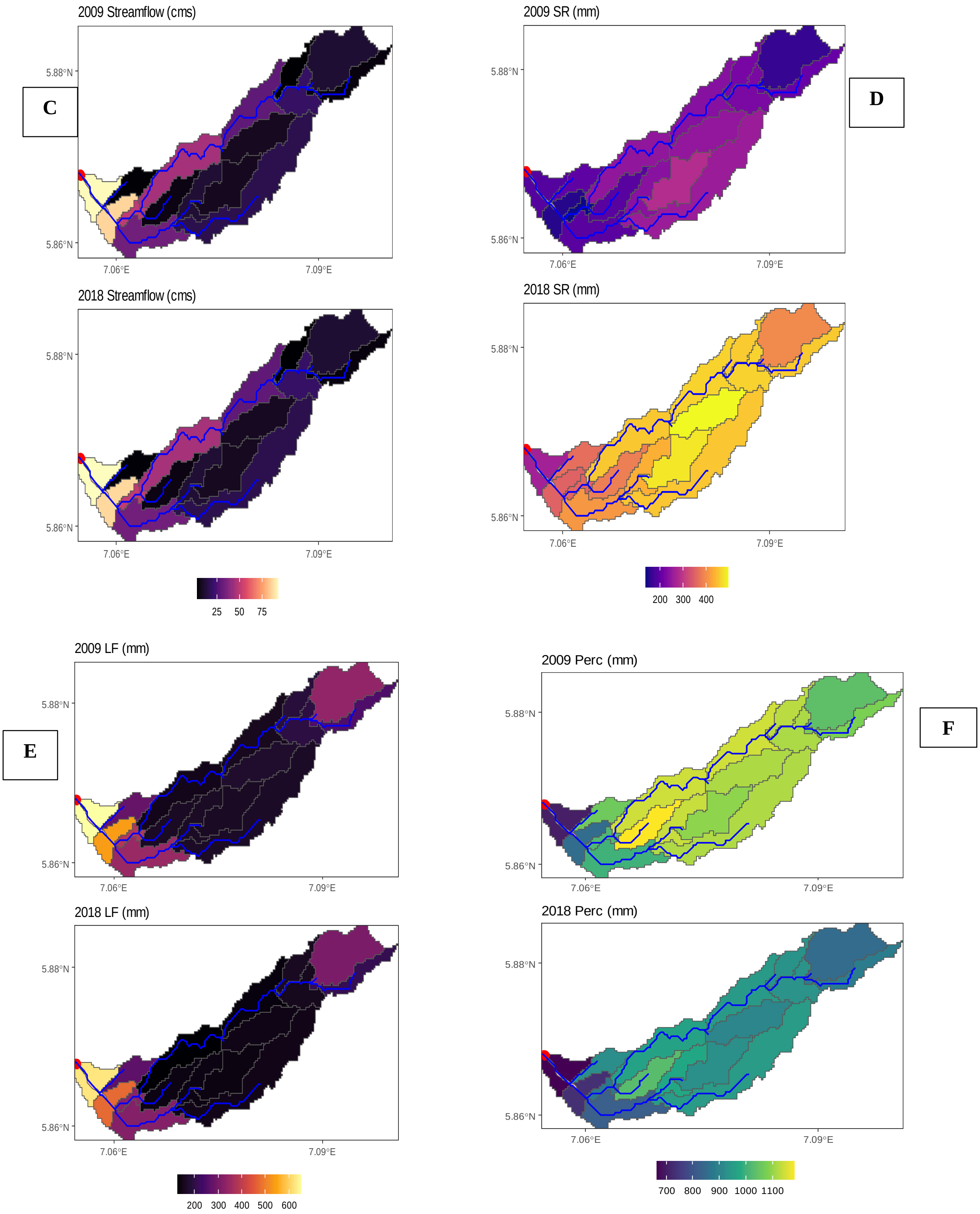
Appendix 5.13 cntd: A, Urualla_gully1 gully watershed. Gully ID, 17. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Total streamflow was 14 and 15 m^3/s for both 2009 and 2018 respectively. D, surface runoff contribution to streamflow showing increased runoff in all but four sub-basins (3, 8, 9, 12). E, lateral flow. Maximum lateral flow was recorded in 2018. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm and 2443 mm for 2018.



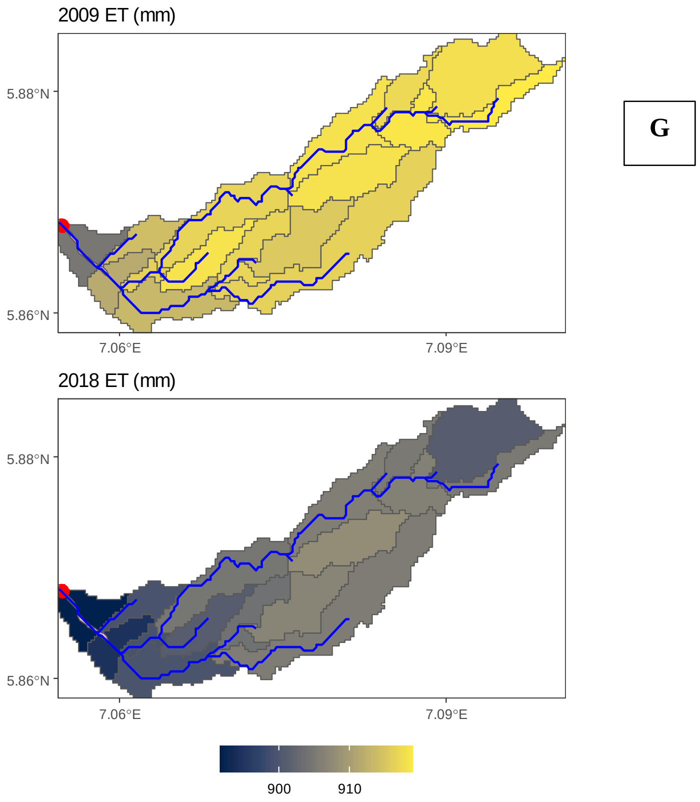
Appendix 5.14: Urualla_gully2 gully watershed.



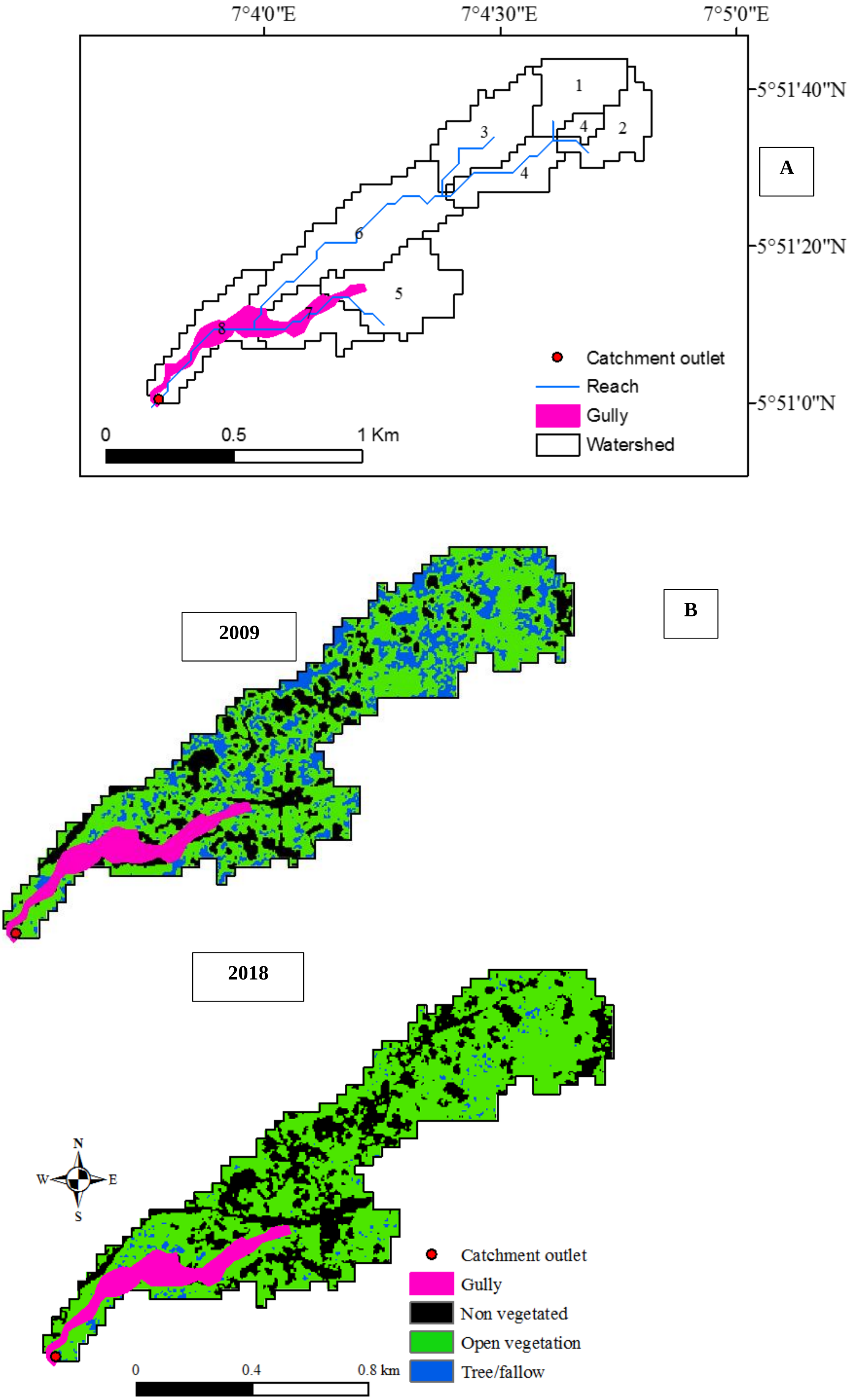
Appendix 5.14 cntd: Urualla_gully2 gully watershed.



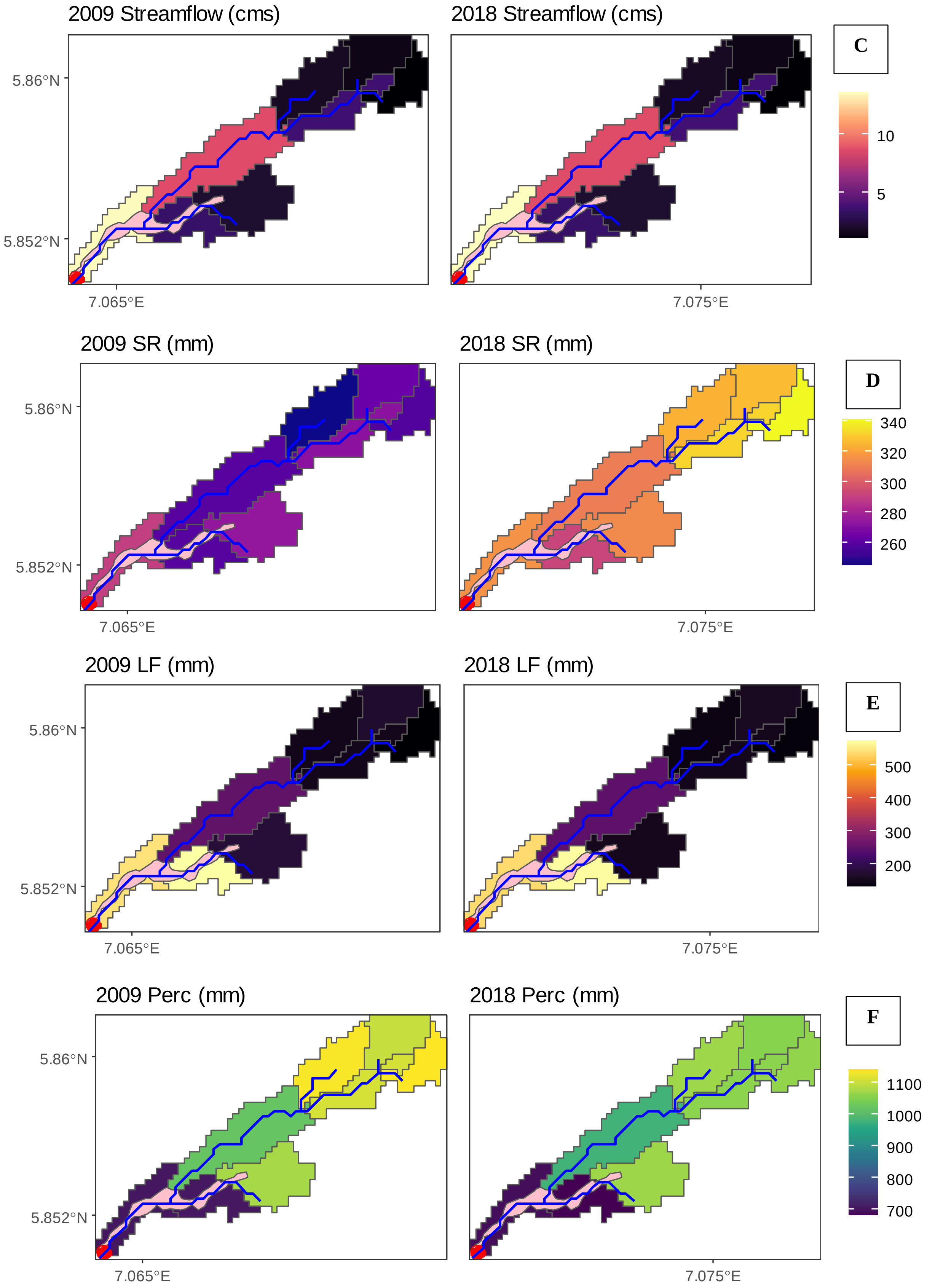
Appendix 5.14 cntd: Urualla_gully2 gully watershed.



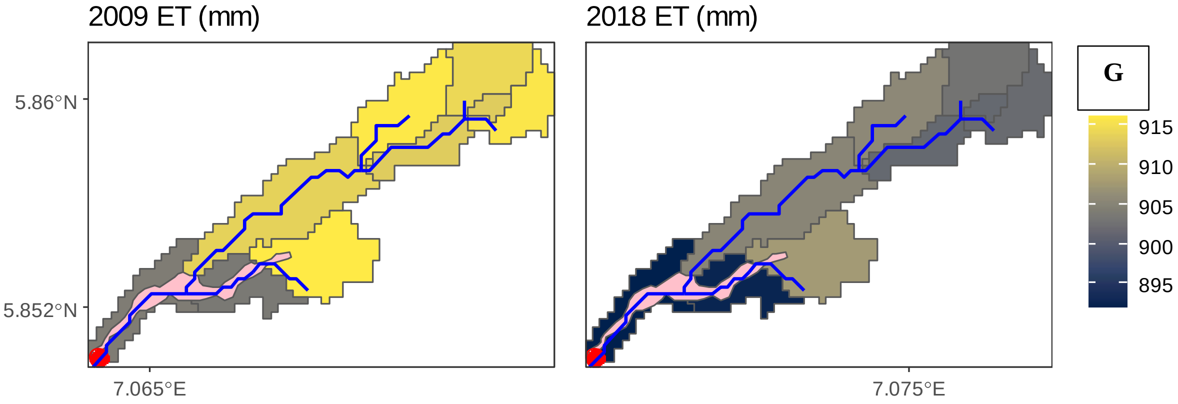
Appendix 5.14 cntd: A, Urualla_gully2 gully watershed. Gully ID, 18. B, Land use change between 2009 and 2018 showing increased non-vegetated surfaces. Non-vegetated area changed from low density to medium between 2009 and 2018. C, streamflow estimates. Total streamflow was 32 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow. Maximum lateral flow was recorded in 2009. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm and 2443 mm for 2018.



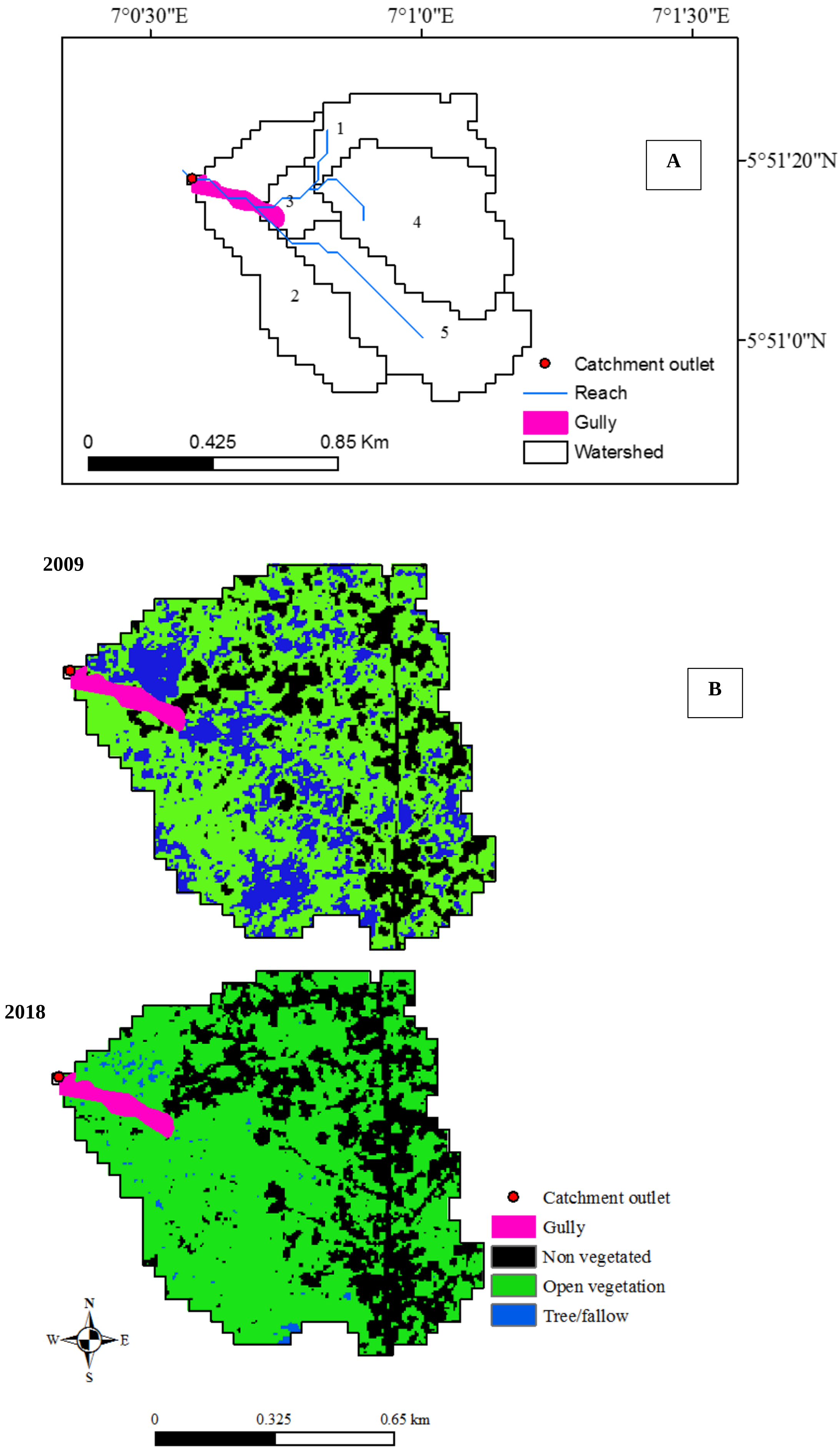
Appendix 5.15: Urualla_gully3 gully watershed.



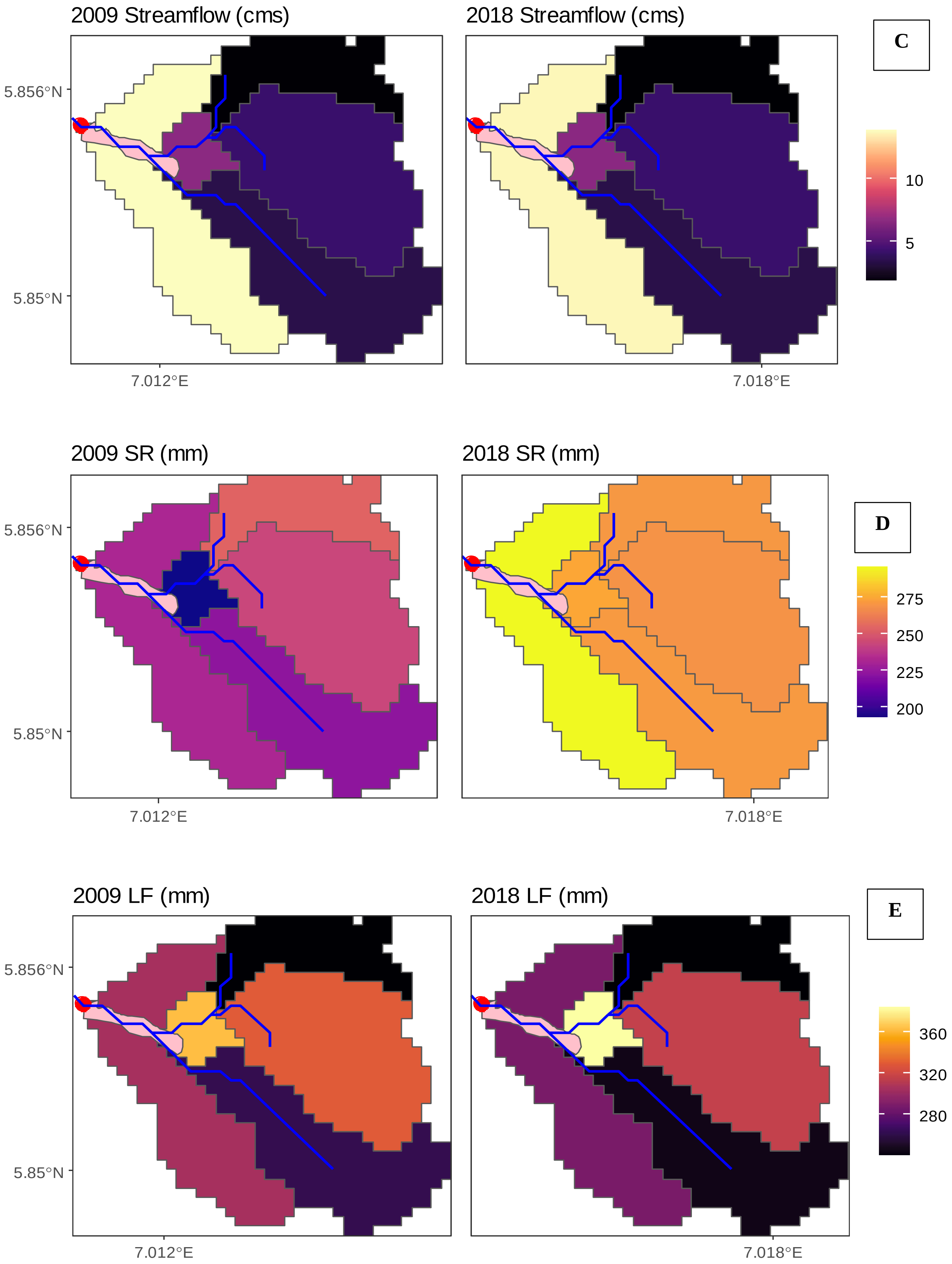
Appendix 5.15 cntd: Urualla_gully3 gully watershed.



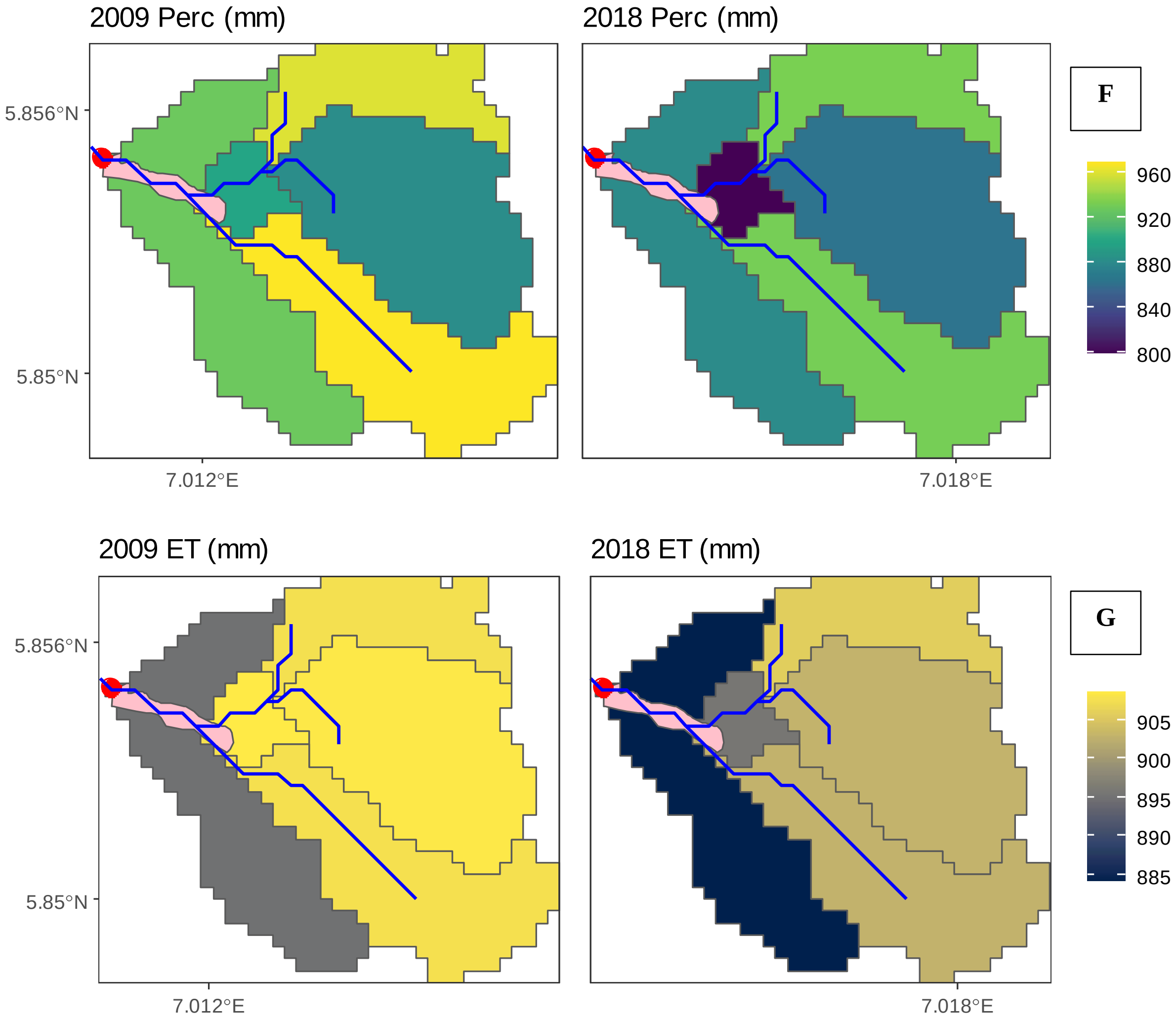
Appendix 5.15 cntd: A, Urualla_gully3 gully watershed. Gully ID, 19. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Total streamflow was 14 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow. Maximum lateral flow was recorded in 2009. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm and 2443 mm for 2018.



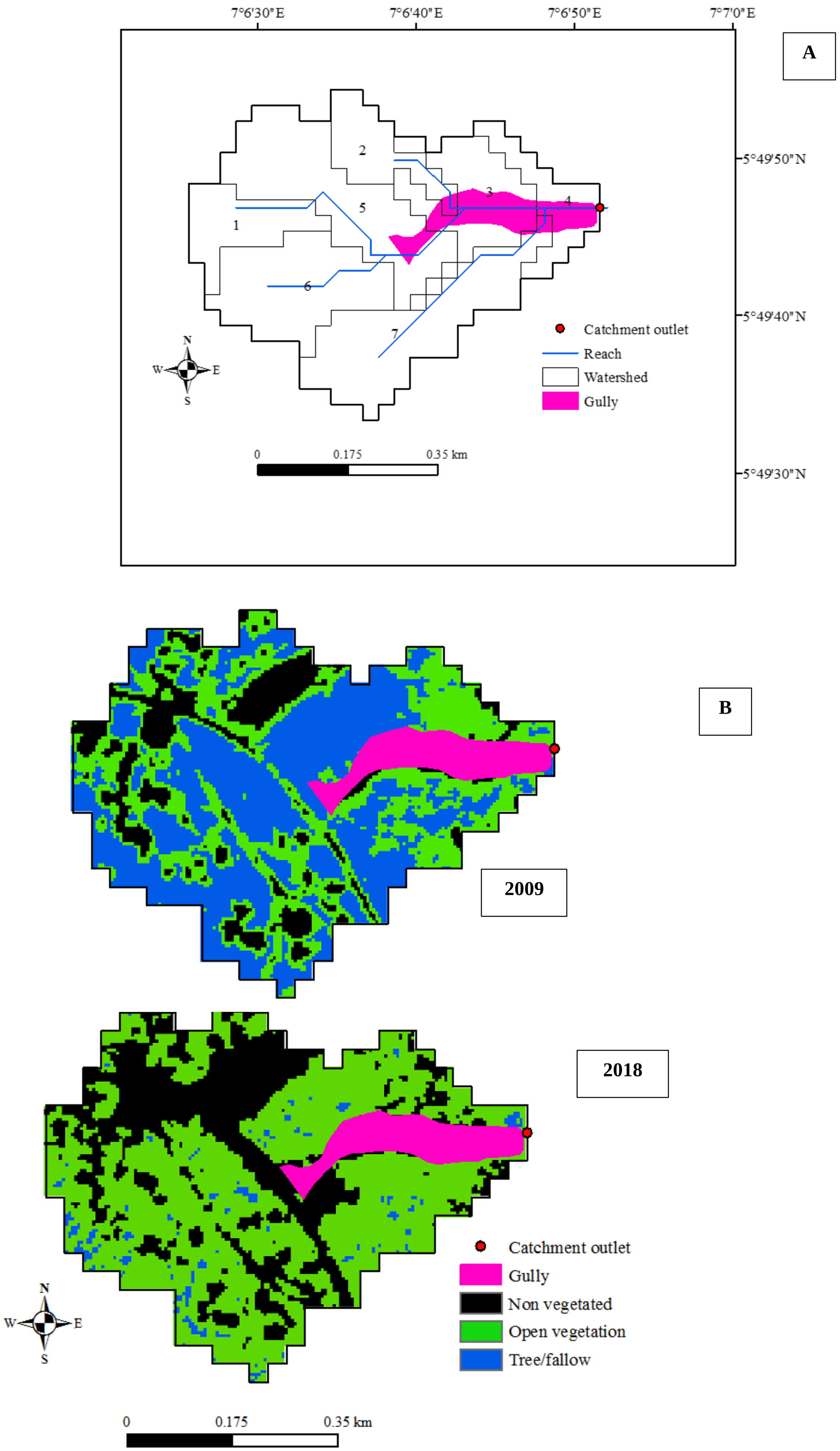
Appendix 5.16: Obibi-Ochasi gully watershed.



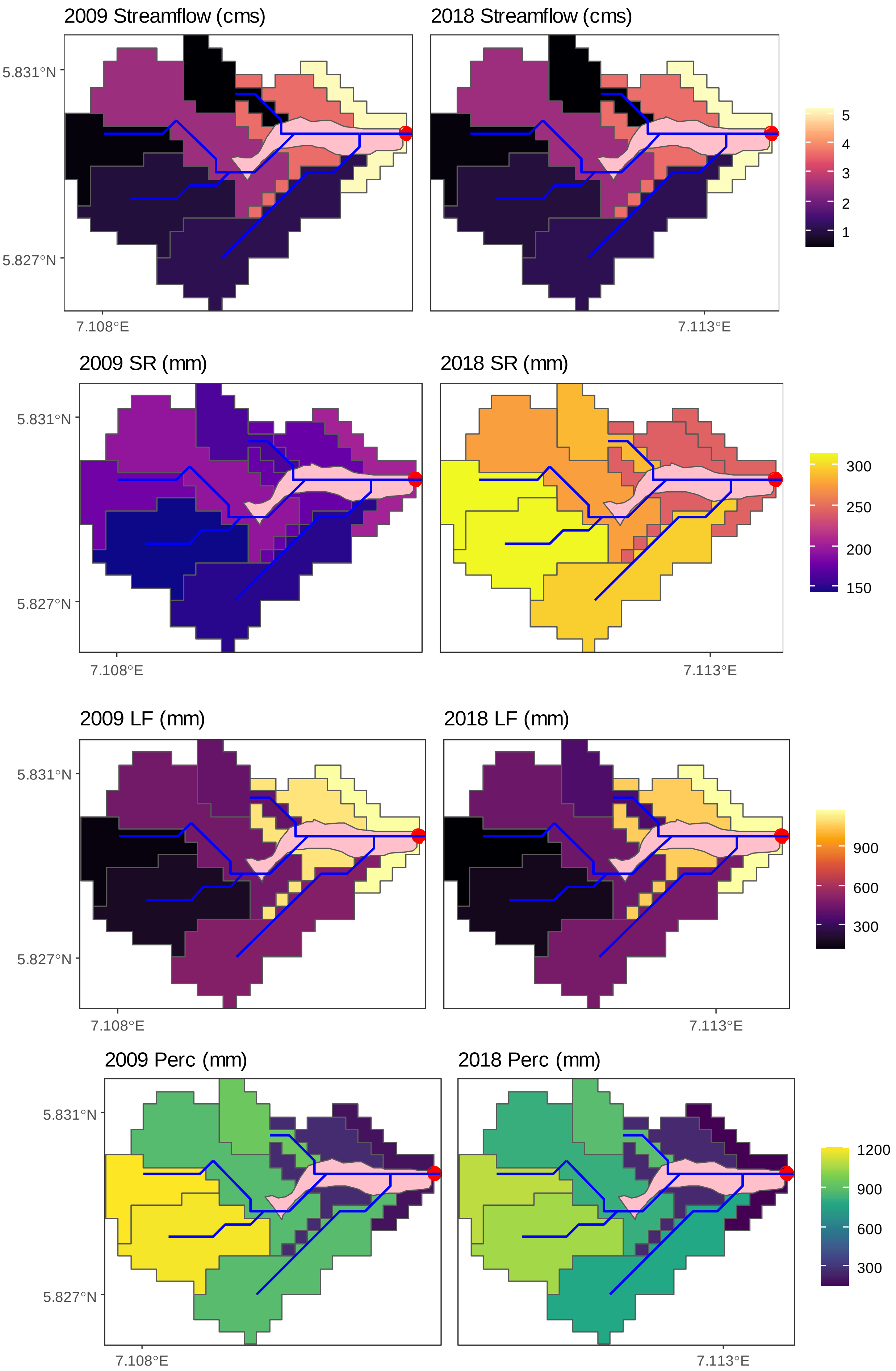
Appendix 5.16 cntd: Obibi-Ochasi gully watershed.



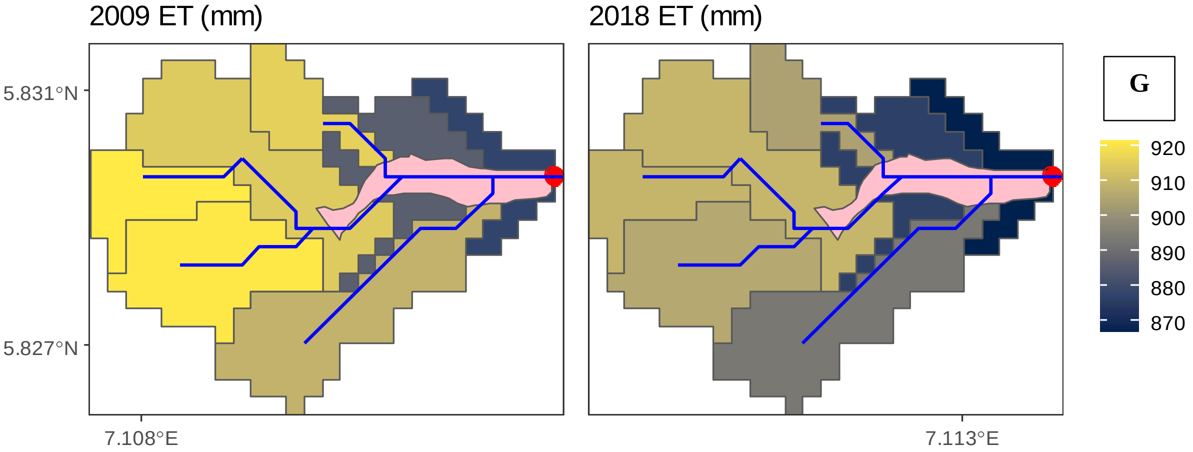
Appendix 5.16 cntd: A, Obibi-Ochasi gully watershed. Gully ID, 39. B, Land use change between 2009 and 2018 showing reduced fallow. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Total streamflow was 3.4 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff. E, lateral flow. Maximum lateral flow was recorded in 2009 except in sub-basin 3. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2364 mm and 2353 mm for 2018.



Appendix 5.17: Umueshi gully watershed.



Appendix 5.17:Umueshi gully watershed.



Appendix 5.17 cntd: A, Umueshi gully watershed. Gully ID, 25. B, Land use change between 2009 and 2018 showing reduced fallow in 2018. Non-vegetated area remained at low density between 2009 and 2018. C, streamflow estimates. Total streamflow was 1 m^3/s for both years. D, surface runoff contribution to streamflow showing increased runoff in 2018. E, lateral flow. Maximum lateral flow was recorded in 2009. F, Percolation. Maximum percolation was recorded in 2009. G, evapotranspiration. 2009 had higher estimates of evapotranspiration. 2009 rainfall = 2447 mm and 2443 mm was generated for 2018.

Appendix 7.1: Invitation to take part in questionnaire survey

Dear Sir/Madam,

I am a PhD student from Durham University researching different types of soil erosion in Orlu Senatorial Zone. I would like to invite you to participate in a survey which will give you an opportunity to discuss the hazards and risks of soil erosion in your autonomous community. The aim of this work is to reduce impacts of these hazards and I will share results of my project with you and the community at the end of my fieldwork. Your comments will be used solely for research purposes and it will take approximately 30 minutes to complete this questionnaire. Your identity will be anonymized, supplied information will remain confidential and collected data will be secured under lock and key or on a computer database accessible by password only for a maximum period of 5 years. You have the right to withdraw your consent at any time during this research.

Thank you,

Ikenna Osumgborogwu

Research student

Questionnaire, please tick as appropriate

Section A: Hazard awareness

1. Do you know what gully erosion is? (If yes, please continue with question 2, if no, please proceed to question 4).

    a) Yes, I know what gully erosion is
    b) Yes, I have heard of gully erosion but I do not know what it is
    c) No, I do not know what gully erosion is
    d) I have never heard of gully erosion before

2. What do you think causes gullying? (please tick all applicable answers)

    a) Act of the gods
    b) Farming techniques
    c) Sand excavation
    d) Others_________________________

3. Do you think gullying can cause harm?

    a) Yes, I strongly believe gullying can cause harm
    b) Yes, I believe gullying can cause harm
    c) I do not know
    d) No, I strongly believe gullying cannot cause harm
    e) No, I believe gullying cannot cause harm

4. Do you know what landslide is? (If yes, please continue with question 5, if no, please proceed to section B)

    a) Yes, it is same with gully erosion
    b) Yes, I have heard about it but I do not know what it is
    c) No idea what landslide is

5. What do you think causes landsliding? (please tick all applicable answers)

    a) Gully erosion
    b) Farming techniques
    c) Sand excavation
    d) Others_________________________

6. Do you think landsliding can cause harm?

    a) Yes, I strongly believe landsliding can cause harm
    b) Yes, I believe landsliding can cause harm
    c) I do not know
    d) No, I strongly believe landsliding cannot cause harm
    e) No, I believe landsliding cannot cause harm

7. Do you think gullying and landsliding are connected?

   a) Yes, I strongly believe gullying and landsliding are connected
   b) Yes, I believe gullying and landsliding are connected
   c) I do not know
   d) No, I strongly believe gullying and landsliding are not connected
   e) No, I believe gullying and landsliding are not connected

Section B: Hazard impacts

8. In the last 10 years (2009 – 2018), are gullies increasing or reducing in this autonomous community?

   a) Gullies are reducing
   b) Gullies are increasing
   c) They are about the same size
   d) I am not sure if they are reducing or increasing

9. In the last 10 years, have you been forced to relocate because of gully erosion?

   a) Yes, I have relocated due to gully erosion
   b) I would have relocated if I had a safe place to go to
   c) No, I have not relocated due to gully erosion
   d) No, but if the gullies continue expanding, I will have to relocate

10. In the last 10 years, have you abandoned a piece of farmland due to gully erosion?

    a) Yes, I left my farm due to gully erosion
    b) I would have abandoned my farm if I had another
    c) No, I have not abandoned my farm due to gully erosion
    d) No, but if the gullies continue expanding, I will have to abandon my farm

11. How many houses/property have been lost in this autonomous community to gully erosion in the last 10 years?

    a) I am not aware of any
    b) 1 – 10
    c) 10 – 11
    d) 11 – 20
    e) > 20

12. How does gully erosion affect you?

    a) Inaccessibility to farm
    b) Severance of communication links
    c) Collapse of houses
    d) Threat to my property
    e) Reduction in farmland
    f) Death of a loved one
    g) Others___________________

13. How has gully erosion affected food production in this autonomous community?
    a) The soil is harder to till

b) There is reduction in yield due to reduction in available land
c) I am scared of going to the farm during periods of heavy rains
d) Others_____________________

14. As an individual, has the problem of gully erosion hindered any developmental project you intended to carry out?

a) Yes, I was forced to abandon a housing project due to gully erosion
b) Yes, I had to stop building a commercial property/farm house due gully erosion
c) No, gullies have not affected any developmental projects of mine
d) I try to avoid areas I feel are prone to gullying
e) Others________________

15. Do you think gully erosion can deter you from embarking on developmental projects in the future?

a) With the rate of gully growth, I will not be able to embark on new developmental projects
b) Gully erosion cannot stop me from building new projects
c) I am not sure
d) Others_______________

Section C: Control measures

Farming techniques

16. Do you farm the land?

a) Yes, I do
b) No, I do not

If yes, please respond to questions 16 – 20, if no, please proceed to question 21

17. How many plots do you have?
Please write__________________

18. What is the ownership status of your farm?
a) Rented
b) Owner
c) Other_______________

19. Has your farm been affected by gully erosion?

a) Yes, I have lost some portions of my farm to gullying
b) No, my farm has not been affected
c) My farm is close to a gully, and soon, probably, it will be affected
d) Others_________________

20. How many years do you leave your land to fallow?

Please write_________________

21. Which other soil-conservation methods do you employ?

Please write________________

Individual effort

22. As an individual, what have you done to reduce hazard impacts of gullying? Please tick all that apply

    a) I do not go to farm during periods of heavy rains
    b) Moved to other farmland
    c) Changed occupation
    d) Tree/grass planting
    e) Hard-engineering projects
    f) Intensified farming on another piece of land
    g) Intensified farming on piece of land affected by gullying
    h) I avoid areas that look unstable
    i) I sand-fill encroaching gullies near my house
    j) I have embarked on hard engineering projects to reduce advancement of gullies
    k) I have not done anything to reduce gullying
    l) Others___________________

23. If you have used hard engineering as a means to reduce gully expansion, how much did it cost you to do this?

    Please write_________________

24. If you have used non-hard engineering as a means to reduce gully expansion, how much did it cost you to do this?

    Please write_________________

25. Is your house insured against gully erosion?

    a) Yes, my house is insured
    b) No, my house is not insured
    c) I will like insurance but cannot afford it
    d) Others_______________________

Community effort

26. As a community affected by gully erosion, what have you done to reduce hazard impacts? Please tick all that apply

    a) Tree planting
    b) We embark on community sand-filling of some gullies
    c) We write to the authorities for help
    d) We use sandbags to reduce gully expansion
    e) We rely on individual effort
    f) There is no community-effort aimed at reducing gully expansion
    g) Others________________

Government, NGOs and INGOs

27. Are there any externally funded project going on in your autonomous community to reduce impacts of gullying? (If no, please go to question 29)

    a) Yes,
    b) No
    If yes, what are they_____________________________________

28. If there are externally funded projects, what are they doing?

    a) Sand-filling gully site
    b) Use of concrete to stabilise gullies
    c) Tree-planting
    d) Others_________________

29. Does the government compensate you for lost farms or property?

    a) Yes, the government pays compensation during big events
    b) No, there is no compensation from the government
    c) They make promises but never deliver
    d) Others__________________

Section D: Demographics

30. Gender [ ] Male [ ] Female [ ] Prefer not to say

31. Age range

    a) 18 – 28
    b) 29 – 39
    c) 40 – 49
    d) 50 – 59
    e) ≥ 60

32. Occupation

    a) Farmer
    b) Civil servant
    c) Private sector employee
    d) Self-employed
    e) Student
    f) Unemployed
    g) Others______________________

33. Household monthly income

    a) Less than N30,000.00
    b) 30 – 60,000.00
    c) 60 – 100,000.00
    d) > 100,000.00
    e) Prefer not to say

Appendix 7.2: Invitation to take part in focus group meeting

Dear Sir/Madam,

I am a PhD student from Durham University researching different types of soil erosion in Orlu Senatorial Zone. I would like to invite you to participate in a focus group meeting which will give you an opportunity to discuss the hazards and risks of soil erosion in your autonomous community. The aim of this work is to reduce impacts of these hazards and I will share results of my project with you and the community at the end of my fieldwork. Your comments will be used solely for research purposes and the meeting will last approximately 60 minutes. Your identity will be anonymized, supplied information will remain confidential and collected data will be secured under lock and key or on a computer database accessible by password only for a maximum period of 5 years. You have the right to withdraw your consent at any time during this research.

Thank you,

Ikenna Osumgborogwu

Research student

Focus group meetings

- Hazard identification
    - Please tell me how long gully erosion has occurred in this community
    - What causes gully erosion in your community?
    - Can you please tell me how big these gullies were 10 years ago?
    - Please tell me the difference between landslides and gullies
    - Please tell me about loss of life or injury in this community due to gully erosion
    - Can you please sketch out gully-landslide interactions for me?
- Hazard mitigation
    - a) Please tell me what you have done to reduce gully hazards
    - b) Please tell me about the effectiveness of these measures you have identified in reducing hazards
    - c) How important is community participation in reducing these hazards? (As a follow on: Do you believe the problem of gullying is beyond your control as a community?)
- Vulnerability and exposure
    - a. Please tell me ways in which you are affected by gully erosion.
    - b. Can you tell me about the history of the growth of this gully?
    - c. Can you please tell me about fallow period in this autonomous community?
- Risk communication
    - a. In what ways are risks of gully erosion communicated to the people?
    - b. Are there local committees tasked with looking at cases of gully erosion? If so, how are they formed? What do they do?
    - c. Have external agencies carried out any programmes on how to reduce gully risks in this autonomous community?
    - d. How did you relate with them during the programme?
- Factors constraining appropriate risk mitigation
    - a. What do you think increases gully hazards in your autonomous community?
    - b. What are the limiting factors to adequate management of gully hazards in your community?
    - c. Please tell me what you think can be done to further reduce risks of gully erosion.
    - d. What would you do differently to reduce these risks?