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SUMMARY OF DOCTORAL THESIS

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Title: Analyzing gully erosion dynamics in the Upper Blue Nile basin, Ethiopia
（エチオピア青ナイル川上流域におけるガリー侵食動態の解析）

Gully erosion is a major cause of land degradation in many regions of the world, including Ethiopia, and accounts for a larger portion (10–95%) of the total soil loss at the catchment scales. The Upper Blue Nile basin is highly affected by soil erosion and soil loss from the basin is estimated at 473 Mt yr^{-1}, of which 10–15% is due to gully erosion.

Despite the significant contributions of gully erosion to the overall sediment yield and land degradation in different regions, research efforts for gully erosion are very limited in Ethiopia particularly in the drought prone regions like the Upper Blue Nile basin. Therefore, this study was aimed to investigate the spatio-temporal distribution, characterization, causes and controlling factors of gully erosion in the Upper Blue Nile basin. The study was conducted in three contrasting agro-ecologies of the basin [i.e., Dibatie (lowland), Aba Gerima (midland), and Guder (highland) watersheds] with three specific objectives: (1) to analyze and quantify the spatio-temporal dynamics of gully lengths and densities; (2) to quantify gully morphological characteristics and gully headcut retreat rates; and (3) to analyze the role of subsurface water on gully headcut and bank retreat. These objectives cover chapters 2–4 of this thesis which includes five chapters summarized as follows:

Chapter 1 explains the introductory section of the study. It presents the study background, problem statement, objectives, and description of the study area based on the existing literatures, field data, and facts. Moreover, it provides summarized descriptions of gully erosion and land degradation, and causing factors and effects of gully erosion on the environment worldwide and in Ethiopia. It then describes the aims of this study and the overall structure of the thesis.

Chapter 2 analyses the spatio-temporal dynamics of gully erosion in three agro-ecologies of the Upper Blue Nile basin of Ethiopia over the last six decades using aerial photographs and satellite images. The aerial photographs were scanned and orthorectified using ENVI 4.3 image analysis software, and gullies were mapped by visual image interpretation in the ArcGIS environment. Rates of increase in gully length in Guder (36.9 m yr^{-1}) and Aba Gerima (33.6 m yr^{-1}) were almost double the rate in Dibatie (17.8 m yr^{-1}) from 1957 to 2016 or 2017, and over the same period, gully density similarly increased by 5.9, 5.4, and 3.7 m ha^{-1} in Guder, Aba Gerima, and Dibatie, respectively. The higher rates in Guder and Aba Gerima reflect the long history of cultivation and human settlement in those sites, whereas agricultural activity became widespread in Dibatie only after implementation of the national resettlement program in the 1980s. Our results indicated that gully erosion was generally higher in the highland (Guder) than in the midland (Aba Gerima) and lowland (Dibatie) agro-ecologies. This result can be attributed to variation in biophysical factors (rainfall characteristics, land use distribution and change, and slope gradient). In addition,

gully distribution was linked to land use and landscape position; gully density was higher in cultivated areas and on gentle slope gradients. The results of this study suggest that careful and site-specific identification of factors controlling gully initiation and development is crucial to design appropriate gully management strategies.

Chapter 3 investigates the morphological characteristics and topographic thresholds of gullies, and estimated the gully headcut retreat rates in three agro-ecologies of the Upper Blue Nile basin of Ethiopia. Gully morphological characteristics were analyzed using data measured in the field, whereas the topographic thresholds were estimated using slope and upslope drainage area. Average annual linear (R_l) and volumetric (V_e) headcut retreat rates were estimated by visual interpretation of very high resolution satellite images in a GIS environment. A significant power relationship, fitted between gully volume (V) and length (L) for the three sites, is $V=8.097\ L^{1.032}$ ($R^2=0.902$, n=94). The average annual R_l and V_e were estimated at 0.86 m yr^{-1} and 6.77 $m^3\ yr^{-1}$ in Guder, 2.09 m yr^{-1} and 19.58 $m^3\ yr^{-1}$ in Aba Gerima, and 3.42 m yr^{-1} and 42.16 $m^3\ yr^{-1}$ in Dibatie. The higher gully headcut retreat rate in Dibatie is mainly related to the highly erodible nature of Vertisols. The coefficients of the slope (S)-drainage area (A) relationship $S=aA^{-b}$ were a=0.219 and b=−0.139 in Guder, a=0.133 and b=−0.234 in Aba Gerima, and a=0.113 and b=−0.216 in Dibatie, indicating that topographic thresholds for gully initiation varied among the agro-ecologies. The results of this study can be used to estimate gully erosion rates and identify areas for gully initiation, thereby supporting the planning of appropriate gully control measures in the study sites and other areas with similar environmental settings.

Chapter 4 aims to better understand the impact of subsurface water processes on gully headcut retreat in the sub-humid highlands (Guder) of Ethiopia. The gully headcut retreat during the 2017 and 2018 rainy season varied from 0.25 to 1.93 m, with mean value of 1.07±0.55 m. The gully cross-sectional area varies from 3.77 to 14.72 m^2, with an average of 8.50±4.41 m^2. The gully headcut volumetric retreat (V_e) values varied from 2.67 to 30.18 m^3, with a mean value of 8.58±7.06 m^3. The soil loss of the 16 individual gullies during 2017 and 2018 ranged from 3.45 to 38.94 t yr^{-1}, with the average soil loss of 11.06±9.11 t yr^{-1}. The water level increased during the rainy season, by the time the strength and the erosion-resistance of the soil decreased, thereby enhancing gully bank collapse. The elevated water level after mid-summer appears less to facilitate the slumping of gully walls. In addition, a weak relationship between gully headcut retreat and the height of the gully head. In conclusion, further investigation is important on controlling factors on gully headcut and bank retreat and develop appropriate gully control measures.

Chapter 5 provides the general synthesis of the whole thesis based on the key findings from Chapters 2–4. The findings of Chapter 2 indicate that gully lengths and densities clearly varied over space and time. Thus, careful site-specific identification of factors controlling gully initiation and development is crucial to develop appropriate management strategies. Chapter 3 demonstrates gully morphological characteristics and gully head headcut retreat rates in three different agro-ecologies, and Chapter 4 investigates subsurface water impact on gully bank and headcut retreat in the tropical humid highland of Ethiopia. The results provide useful information to estimate gully headcut retreat rates, identify areas for gully initiation, and to support the planning of appropriate gully control measures in the Upper Blue Nile basin of Ethiopia and other areas with similar environmental settings.