DOCUMENTING RECENT HUMAN INFLUENCES USING REMOTE SENSING TECHNIQUES ON THE TEKES RIVER ALLUVIAL FAN, XINJIANG, CHINA

by

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ABSTRACT

Documenting recent human influences using remote sensing techniques on the Tekes River Alluvial Fan, Xinjiang, China

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The Tekes River alluvial fan is located in Xinjiang Province which has an arid to semi-arid climate as well as a historically unpredictable precipitation rate. Further, increasing population and urbanization means that all water resources must be used efficiently. The Tekes River alluvial fan has had a vast amount of human influence in recent decades in the form of dam construction, irrigation and agriculture expansion. Although development on and surrounding the Tekes River alluvial fan is apparent, there is a lack of research on how these human impacts have affected the fan. The primary objective of this project is to use remotely sensed image analysis to document the human influence that has occurred to the Tekes River alluvial fan. A 31-year time series (1990-2021) was created using Landsat imagery from 1990 – 2021. The results have found that four dams have been constructed upstream from the fan, irrigation canal length had increased by approximately 400 km, and agricultural fields had increased by approximately 250 km^2 between 1990 to 2021. Average seasonal NDVI values were calculated on agricultural fields and compared to natural vegetation in the area for seven dates in 2021. The results do not show great observable differences between agricultural field and natural vegetation cover. However, these results are limited temporally and spatially. It is possible that human influence will be affected seasonal NDVI variation on the fan but there has not been enough time between development and the time of the research. Further research should continue to document and test NDVI as well as consider measuring groundwater levels to build upon this research and provide a greater understanding of the anthropogenic impacts on the fan.

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CHAPTER 1

Introduction

1.1 Overview of the Project

Anthropogenic impacts have influenced numerous natural processes largely through the acceleration of climate change driven by a rapidly increasing global population. Climate change can alter average temperatures, precipitation patterns, storm surge frequency, as well as increased risks of drought, all of which have cascading effects on ecosystem functions. Humans must adapt to a changing climate while also population and industrial development continues in many parts of the world. Some regions require more drastic development strategies depending on the natural characteristics of the area. For example, semi-arid to arid regions are defined by low annual precipitation rates, 25 cm/yr or less in arid regions, and between 25 – 50 cm/yr in semi-arid regions (Ren et al., 2017). China is defined as having a semi-arid to arid climate (annual precipitation is less than 500 mm/yr), and high evapotranspiration rates (Wu et al., 2014). Moreover, the annual mean surface temperature has increased by 1.1 C^o over the past 115 years, the population of China has been steadily increasing (Ren et al., 2017). Rapid economic growth and urbanization in China as stressed many of China’s water resources to the extent that many river basins are experiencing water shortages (Wu et al., 2014).

Limited water resources in China have increased the trade-off between economic development and ecosystem services. The development of infrastructure to sustain population and economic growth, has led China to heavily rely on their water resources. Most (94%) of the water use in Xinjiang, China's largest province, is used for agricultural irrigation (Zhang et., 2018). Although irrigation allows for steady agriculture yield when precipitation is inconsistent, the practice greatly alters the landscape.

The focus of this project is the Tekes River alluvial fan in Xinjiang, China. This landform has seen a vast amount of human development in recent decades in an attempt to produce reliable agricultural yields. Although development on the fan has been established rapidly, there is a lack supporting literature on how development may be altering the natural processes of the fan and surrounding area. In a sensitive climatic region understanding the environmental effects of development is crucial in order to avoid issues such as overexploitation of water resources, land use degradation and more. The goal of this research is to provide the first known documentation of the human involvement affecting the Tekes River alluvial fan.

1.2 Background on Alluvial Fans

Alluvial fans have been studied from the perspective of several different disciplines such as geology, environmental science and sustainability, and geography. This has led to a plethora of resources regarding alluvial fans; however, Blair et al. (2009) state that fan research was not common until the 1960s, but has greatly increased since then, particularly in semi-arid to arid regions. The reasons for this being that alluvial fans must be understood by many professions for natural hazard mitigation, understanding hydrologic regimes, and understanding climate change (Blair et al., 2009). Presently, many regions with a semi-arid to arid climate are experiencing water scarcity issues, therefore filling-in the knowledge gap in these areas is pressing.

1.2.1 Definition of Alluvial Fan

Alluvial fans are landforms that link the highly erosional hillslope, where sediment is produced, the fluvial realm where sediment is transported, and the depositional valley floor realms of geomorphology. A comprehensive definition of an alluvial fan is provided by Kostaschuk et al. (1987; 366): “An alluvial fan is a fluvial and/or debris flow deposit, with a semi-conical surface, radiating downslope from an apex where a confined channel emerges from an upland source area”. Source areas, also called upper catchment areas or drainage basins, are usually found in mountainous regions that catch precipitation and/or glacial meltwater. Water flows down slope in a channel confined by the topography before leaving the drainage basin. The channel becomes suddenly unconfined, and the gradient greatly reduces at the mountain base which allows flow to expand laterally (Bowman, 2019). This marks location known as the apex which is the beginning of the alluvial fan (Kostachuck et al., 1987).

Flow velocity is greatly reduced at the apex due to the unconfinement and decrease in gradient; therefore, the flow loses its capacity to transport sediment and rapid deposition of relatively larger sediment occurs (Blair et al., 2009). Beyond the apex, flow velocity naturally continues to decrease, and finer grain sediment (called alluvium) is deposited, creating the cone-shaped landform for which alluvial fans are known for (Kostachuck et al., 1987). This depositional style also means that there is a fining outward pattern of sediment on the fan surface from the apex to the toe (which is end of the fan) (Harvey, 2011). The distributary channels on fan surfaces also performs sorting, because distal channels can transport fine grain sediment only whereas the main channel, which terminates more mediately, is able to transport coarser sands (Bowman, 2019).

1.2.2 Processes that Occur on Alluvial Fans

Blair et al. (2009) describes key features of a fan as being the apex, the main channel, the intersection point, active depositional lobes, and headward-eroding gullies. The main channel, as described by Harvey (2010), is the downslope extension of the upper catchment feeder channel which terminates in the medial part of the fan or intersection point. Active depositional lobes are downslope from the intersection point where sediment is continually being deposited by active fan channels. Older surfaces are found laterally from the active deposition lobes; these areas are not currently receiving sediment or flow and if undistributed for long enough can host vegetation (Nanson, 2013). Vegetation stabilizes older surfaces creating stable islands for which flow must deviate around, thereby prompting an anastomosing pattern on the fan (Nanson, 2013). It is important to understand the different aspects of fans, and how they are formed in order to be able to understand their dynamics and future evaluation.

1.2.3 Types of Alluvial Fans

Alluvial fans can be broadly differentiated into two types, debris flow dominated or fluvial dominated fans (Fath et al., 2018). This is mainly dependent on the water to sediment ratio and the grain size of the material being transported from the drainage basin; these factors affect how the material is deposited (Harvey, 2010). The water: sediment ratio, as described by Harvey (2011), is usually higher with a larger drainage basin. This is because although larger drainage basins contain more sediment, they tend to hold coarser grained sediment, which increases porosity, meaning a larger amount of water can reside in the pore space between grains. A low water: sediment ratio and a smaller drainage basin will result in a fan dominated by debris-flow processes (Harvey, 2010).

The process to create debris flow fans is an upstream mass failure caused by the presence of gravity acting on an accumulation of alluvium on slopes (Nanson, 2013). A low water to sediment ratio and a higher clay content, as Fath et al. (2018) explains, will increase the strength of the material and resist flow which is referred to as cohesive debris flows. A higher water content with a lower clay content will behave more fluidlike, this is referred to as a wet debris flow. These different prosses are controlled by the type of sediment present in the system and will ultimately determine the sedimentology of the fans surface.

Kostaschuk et al. (1987) observed that debris flow fans have more angular, poorly sorted grains ranging from clay to boulders due to the shorter a transport time. Therefore, the fans that are produced from debris flow processes are relatively shorter, thicker, steeper, and have less channelized flow than fluvial dominated fans.

Fluvial dominated fans have a relatively higher water to sediment ratio; therefore, sediment is transported via stream-flow processes. In this case, flow velocity is higher allowing active fan channels to incise into the surface creating channelized flow. The surface of a fluvially dominated alluvial fan will have many wide well-defined channels across the fan surface and this may be via a single threaded network, or a braided channel network, if the fan is large enough and has a low angle gradient (Nanson, 2013). Parker at al. (1998) explains that channels on fluvial flow fans man meander, split or become a fully interconnected.

A fan dominated by fluvial processes will show rounded well sorted grains in well defined, gravel-bed channels (Kostaschuck et al., 1987). Fluvial fans tend to be larger in size due to the larger drainage basin (Kostaschuck et al., 1987), which usually allow for a greater amount of sediment supply. In this situation, fine grain sediment is suspended in the water and coarse grain sediment moves via traction along the bed (Harvey, 2011). Fluvial dominated fans are built up by the successive aggradation which can cause active fan channels to become choked (Bowman, 2019). In this case, one channel becomes blocked by an accumulation of sediment therefore blocking flow and causing a channel switch this is known as avulsion (Taylor, 1978). This typically occurs distally from the intersection point and may cause channels to widen and loose power and create depositional bars which show a distally fining succession towards the toe of the fan (Harvey, 2010).

The alluvial fan in this study is dominated by fluvial processes but understanding the mechanisms of both fluvial and debris flow fans is important because fans can evolve depending on the water to sediment ratio. This concept is best portrayed in Figure 1.1 by Harvey (2010), whereby an increase in water supply leads to progradation, or the fan builds outward and increases in length, or dissection/incision meaning the flow of water is able to cut into the sediment, increasing in channel depth and narrowness due to a higher water to sediment ratio. Deposition will occur if

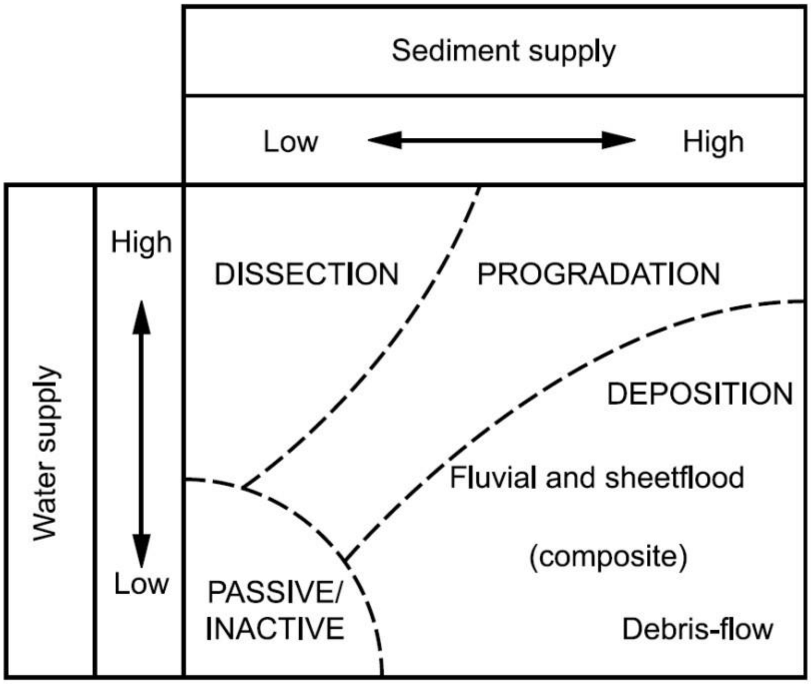


Figure 1.1: Diagram showing the shift in state alluvial fans will undergo depending on sediment supply and water supply (Harvey, 2010, Figure 6.4).

sediment supply increases and water supply decreases and a fan will become inactive if both decrease. Unconfined sheetflows (as seen in Figure 1.1) is another process that can occur on alluvial fans. These are mainly instances when a sediment-rich flood occurs upstream which inundates the fan. Sheetflows do not have the velocity or water content needed to down-cut into sediment; therefore, will not show any sign of incision and no channels will be formed from this process (Parker et al., 1998). These events bring sudden new introductions of sediment to the fan surface.

Fan gradient is the steepness of the fan surface distally from the apex, and is a key morphological property that influences depositional styles on fan surfaces (Harvey, 2010). The minimum transport threshold as described by Harvey in 2010, is the point in which flow loses the capacity to transport sediment and deposition will occur when transporting power falls beneath this point. The minimum threshold for deposition in debris flows affects how far flow can travel, therefore the length of the fan. For debris flow fans, the minimum transport threshold is dependent on several factors including, internal friction (due to grain size and water: sediment ratio), the roughness of the surface for which it flows over as well as fan gradient. Debris flows having less transport power and flow velocity will stop moving at higher gradients compared to fluvial processes and sheetflows will stop at a higher gradient compared to channelized flow for the same reason (Harvey, 2010). As Harvey (2010) explains, for fans created by fluvial processes the minimum threshold to transport is dependent on grain size, stream power or velocity of flow, channel depth as well as fan gradient.

1.2.4 Conditions Required for Fan Development

According to Blair et al. (2009) there are a few key criteria that must be present for the development of an alluvial fan. Firstly, there must be a setting where an upland catchment area or source area drains into a lowland valley. These settings are commonly found in areas where tectonic activity has a created an upland topographical high near a relatively low area, where differential erosion has caused one area to lose its elevation or where turbidity channels enter a valley (Blair et al., 2009; Harvey, 2010).

Secondly, the sediment supply must be sufficient enough to be carried downslope and make up the fan surface. Sediment production takes time, as weathering is a process that gradually breaks down bedrock either mechanically or chemically which then can become entrained and transported (Blair & MacPherson, 2009). However, the presence of relief, which is the difference in elevation between the highest and the lowest topographic point in an area, increases sediment yield exponentially. Therefore, Blair et al. (2009) state that faulted mountain fronts are ideal settings for fan development. They are usually areas with high relief and are efficient sediment producers for upper catchment areas. The fracturing that occurs in these areas exposes new rock and relief is maintained.

The lithology of the fan surface is dependent on the lithology of the upper catchment area. Bowman (2019) explains that weathering and erosion cause new rock lithologies to be exposed due to tectonic uplift; consequently, the new stratigraphy will be reflected on the fan surface.

Non-tectonic catchments such as those catchment areas that are produced in paraglacial valleys, can have enough previously deposited sediment to develop a fan, but sediment supply in these types of locations may become depleted (Blair & MacPherson, 2019). The last two settings of catchment areas lead to limited fan evolution as they lack the ability to maintain relief and sediment supply.

The last criteria needed for alluvial fan development is the presence of what Blair et al. (2019) describe as a triggering mechanism. A triggering mechanism mainly causes the transport of sediment from the upper catchment to the fan surface. It is usually in the form of high amounts of water input, either from a rapid or prolonged precipitation event, or from high amounts of ice or snow melt due to a sudden failure of a nearby natural dam (Blair & MacPherson, 2019). These are what Blair et al. (2019) constitute as primary processes, the processes by which alluvial fans are produced on Earth.

Beyond the catchment area, flow must lose its competency, meaning its ability to entrain sediment, and lose its capacity to transport before reaching the fan surface. This can either occur due to a great decrease in gradient at the apex or a large decrease in flow velocity and depth due to the sudden lateral expansion that occurs when exiting the apex. A decrease in energy results in large boulders, with an average diameter of 350 cm, being deposited at the apex and an average grain diameter of 15 cm at the toe (Bull, 1977). A study completed by Blair and MacPherson in 2009 looked at 132 fans in Death Valley California and showed that fan development is favoured more when lateral expansion is the main reason for flow to lose its competency and capacity instead of slope gradient decrease. Therefore, settings in which allow for a large amount of unconfinement will more likely create alluvial fans rather confined areas.

Alluvial fans can be understood by considering a few important criteria such as size of the catchment area, fan gradient and the water to sediment ratio. These are fundamental in order to understand how human development can affect these processes. Furthermore, alluvial fans have the ability to preserve large environmental changes within their sedimentary sequences, causing them to be even more crucial landforms to study.

1.2.5 Importance of Alluvial Fans

Alluvial fans are unique landforms that are very sensitive to their environment and processes are greatly affected by environmental change. This is important as fans give a relatively quick example of how a seemly insignificant environmental change can lead to very drastic change in alluvial fan processes. As well, alluvial fans have the ability to preserve evidence of past environmental and climate change events and allow for researchers to relatively and absolutely date sedimentary sequences on fan surfaces, giving insights to past environmental changes.

1.2.5.2 Preservation of Sedimentary Sequences

Large environmental shifts between and within different geologic periods have been recorded in alluvial fan sedimentary sequences, and can have the ability to shift fan regimes. For example, Harvey (2010) studied fans in southwest Spain and determined that they were in phases of aggradation (high water and sediment supply) due to the melting from large glaciers created in the Pleistocene epoch (2.6 million to 12,000 years ago). Melting of glaciers which feed into the drain basin means that large amounts of not only water, but sediment can be released and transported down to the fan. Periods such as this can cause a debris flow dominated fans to switch to a fluvial dominated fan (Kostaschuk et al., 1987). Another result of a strong aggrading fan is an increase in the sorting of sediment on the proximal areas of the fan (Harvey, 2010). In the Scottish Highlands, Harvey (2011) studied an alluvial fan which, like the Spanish fan, was in a state of strong aggradation prompted by a paraglacial melting event in the Early Holocene (12,000 years ago to present). However, this fan also showed evidence of progradation or advancement distally, coinciding with an increased water supply in the late Holocene. According to these events and the relative time periods, these changes to the fan regime likely reflected the climate change event associated with the 'Little Ice Age' in the seventeenth and eighteenth centuries. This shows how on a large timescale such as these major environmental changes lead to large regime changes on the alluvial in the area.

Alluvial fan sediment sequences can, especially in semi-arid to arid regions, preserve a record of geomorphic responses to Quaternary (the period containing the Pleistocene and Holocene epochs) climate changes. Using a multiparameter approach as described by Harvey et al. (1999), relative dating of fan sequences can be done and compared with known Quaternary climate change events to understand if the changes to fan sediment are a result of the changes in the environment. For example, Harvey et al., (1999) was able to observe regime changes preserved in sedimentary sequences on alluvial fans in the Mojave Desert that coincided with major global climate change events. During the last glacial maximum, the fan was in a period of strong aggradation which slowed during a climatic transition at the end of the Pleistocene epoch. Then, intermittent phases of strong aggradation can be seen again which coincided with the climate change events seen during the beginning of the Holocene. Being that the study area for this research is set in a semi-arid to arid climate, preservation of sediment sequences such as what was seen in Mojave could be seen in Tekes.

Relative dating of fan surfaces can be achieved and has been extensively studied in the last few decades by analyses of fan surface characteristics such as desert pavements and soil development (Ren et al., 2011). For example, areas on the fan surface that shows desert pavement is evidence that this area has been inactive for quite some time (Bowman, 2019). Absolute dating can be achieved for alluvial fans by comparing the stratigraphic relationships between the fan and spatially close landforms for which the date is already determined such as lake shoreline features (Ren et al., 2011).

1.2.5.2 Contribution to the Hydrological Cycle

Depending on the grain size, alluvial fans can be important groundwater reservoirs. In debris flow dominated fans the hydraulic conductivity, which is the ability to transmit water through pore spaces, is low in the proximal areas of the fan and highest near the mid-fan (Bowman, 2019). In fluvial dominated fans, the hydraulic conductivity increases with larger grain sizes (Bowman, 2019); therefore, there is an increase in hydrologic conductivity near the apex that decreases down-fan. Infiltration is highest in incised channels which occur in proximal areas of the fan when flow velocity is greatest (Parker et al., 2012). Furthermore, distal fan channels are comprised of finer grain material which naturally have lower transmissivity and storage abilities (Bowman, 2019). The heterogeneity of hydrologic conductivity on fans can provide overall consistent groundwater recharge to unconfined aquifers (Bowman, 2019).

1.2.5.3 Anthropogenic Dependence on Alluvial Fans

Consistent sediment supply, a high degree of sorting, and relatively consistent water supply on alluvial fans creates an ideal setting for agriculture growth. Furthermore, fans are found in mountainous areas where agriculturally suitable land is commonly limited. Because of this, alluvial fans can be very valuable crop lands, this being exacerbated in regions where water resources are limited.

In semi-arid to arid regions where evapotranspiration exceeds precipitation, run-off issues of soil salinity and desertification arise, and importance is placed on water resources such as alluvial fans. Guo et al. (2019) mentions in arid regions, river water is unreliable compared to groundwater, but groundwater tends to be overexploited. This is true for China as more than 40% of the water used here is sourced from groundwater (Currell et al., 2020). Currell et al. (2020) found that groundwater facilities have been developing in the agricultural sector in

Northern China since the late 1950s and this has allowed for the development and expansion of agriculture in marginal arid environments where growing crops is very difficult. However, this can lead to the pumping of groundwater which affects the recharge rates and in arid regions there is already little evidence of deep aquifers being recharged or replenished (Hu et al., 2015).

1.3 Anthropogenic Influences on River Systems and Alluvial Fans

1.3.1 Damming of Rivers

In semi arid to arid regions especially it is common for rivers to be dammed in order to store water for low precipitation times. Dams, however, drastically alter the mechanism of a river and corresponding alluvial fan. Nurtazin et al. (2019) studied the effects of constructing a the Kapchagai dam and reservoir on the Ili River in Kazakhstan in 1970. This hydropower dam has had a major impact on the annual cycle of flow rate, decreasing flow in the summer and increasing flow in the winter when the water is released from the dam. Flow rate decreased by an average of 102 m^3/s after the construction of the Kapchagai dam (Nurtazin et al., 2019). Currell et al. (2020) explains that dams hold and divert water runoff in its reservoirs in order to supply drier areas with water or to be used for irrigation agriculture. This leads to a decrease in surface water runoff and infiltration which would recharge deep aquifers because the reservoir holds water that normally would have flown over the surface during a flood event. Furthermore, Deng et al. (2016) found strong evidence to suggest there is little to no present-day recharge to the deep aquifers in Northern China which historically were thought of as a renewable source of water.

1.3.2 Irrigation and Agriculture on Alluvial Fans

Reservoirs allow for a more predictable water supply for farmers, therefore following the construction of dams there is usually an increase in agricultural development in the surrounding area. Guo et al. (2019) researched the Dunhuang alluvial fan which is supplied by the Dunhuang River in Northwestern China. A hydropower dam was constructed on the river in 1975 and a consequent reservoir was created which now holds a large portion of the river water. 30 years since the dam was constructed there has been a vast increase in irrigated farmland from 8,900 ha to over 26,000 ha, and the number of freshwater wells increased from 400 to over 3,000 (Guo et al., 2019). Now, Guo et al. (2019) estimates that 93% of the river water is being used as irrigation water, and of that, 35% of this irrigated water infiltrates the surface and becomes a dominate source of groundwater recharge. However, irrigation water as a source of groundwater recharge can be problematic. Currel et al. (2020) states irrigation water tends to be higher in salinity and concentrations of nitrates and other contaminants. These can affect the quality of the groundwater in unconfined aquifers. Humans can drastically alter environmental processes such as the mechanisms of the hydrologic cycle and groundwater quality through the development of agricultural.

1.3.3 Possible Effects of Irrigation on Vegetation

As seen earlier, alluvial fans are sensitive landforms that will reflect environmental changes. This also includes human-induced environmental change such as dam construction. However, there is a lack of research regarding how alluvial fans could be affected by the damming of their rivers.

There needs to be a clear understanding of how human infrastructure such as dams will affect the natural processes of the hydrologic cycle. This is increasingly important as populations are increasing and humans will inevitably require more freshwater, especially in arid regions. Alluvial fans have been shown to be able to provide an ideal setting for agricultural development but what implications does this have on the fan? Although this is a pressing issue there is little literature on how human development affects alluvial fans. The Tekes River alluvial fan is an example of a fan whose freshwaters are being taken advantage of for agricultural practices; but there is a gap in the research as what the effects of this might be.

One way to assess the health of vegetation is to use the normalized difference vegetation index (NDVI) which is analyzed in remote sensing to quantify the amount of chlorophyll in plants. Healthier vegetation will have more chlorophyll and therefore, appear relatively greener than vegetation that is stressed and appearing browner or red. Satellites detect the amount of red and near infrared light that plants are emitting, vegetation will emit more near infrared light if they are green/healthy. From this, a simple calculation can be done where the amount of infrared light is normalized to the amount of red light and a single NDVI value is obtained. NDVI values range from -1 to +1 with values closer to +1 representing healthier vegetation. NDVI allows for the quality of vegetation to compared to vegetation at different locations and over time. Using NDVI could provide insights to alterations in seasonal vegetation health cycles as a result of human intervention.

1.4. The Study Area

Literature written about the Tekes River region has been from a geographic and environmental perspective, with aspects relating to socioeconomics and politics. However, there is no accessible research regarding the Tekes River alluvial fan specifically. The Tekes River is a primary river fed by glacial melts and precipitation; originating from the Hantenri Peak in the Tian Shan Mountains in Xinjiang province, China (Xu et al., 2015). The Tekes River alluvial fan is located in the hinterland of Xinjiang and is surrounded by three mountain ranges with two basins in between (Sun et al., 2010). As well, complex topography in China shows higher elevations in the east that gradually but consistently decrease towards the west (Sun et al., 2010; Xu et al., 2015; Zhung et al., 2011; Zhung et al., 2018), resulting in unevenly distributed natural resources (Han et al., 2020). For example, Currell et al. (2012) found that Northern China contains about half of the population of China (1.4 billion in 2020; Han et al., 2020), but has less than 15% of China's available surface water. Furthermore, according to Xu et al. (2020) irrigation infrastructure is very difficult to maintain in Northwestern China because of the topography. This issue is exacerbated by the semi-arid to arid climate. The climate is partly a result of the unique topography creating an enclosed ecosystem with widespread forest and vast grasslands in the Tekes region known as the “the small Jiangnan of Xinjiang” (Xu et al., 2015). However, Zhang et al. (2011) found that in the last 20 years there has been rapid development of socioeconomic and eco-environmental problems, such as overgrazing, grassland degradation, geological disasters, and increased soil erosion.

The Tekes River flows through the steepest reaches of the Tian Shan Mountains before being joined by the tributary Kash river then later creating the Tekes River alluvial fan. The fan terminates into the Kunes River which eventually turns into the Ili River and flows into Kazakhstan, draining into Lake Balkhash. This means that that the Tekes River system is indirectly an international river. Infrastructure built on the Tekes River or alluvial fan could affect the Kunes River and the Ili River in Kazakhstan.

1.4.1 Political History of the Tekes Region

Post-1949, the newly appointed Chinese Communist government initiated a major effort to enlarge its agricultural production and encourage settlement in the Tekes and Ili regions of China (Wiens, 1969). New irrigation canals were dug and extended, resulting in a tripling of cultivated area from 1949 to 1964. Furthermore, four concrete sluice gates were constructed to regulate flow and improve irrigation in the Tekes and Ili regions. Primary crops included maize, rice, millet, wheat and cotton (Wiens, 1969). The increase in agricultural production created a shift from nomadic peoples to a sedentary type of lifestyle. Therefore, construction of streets, city sections and some large three storied buildings were development (Wiens, 1969). Pastoralism came to an end and an agricultural dominance and increased urbanization became the norm for the Tekes and Ili River valley regions.

1.5 Research Objectives

This project will document the anthropogenic developments that have occurred on the Tekes River alluvial fan in recent decades. This will be completed by creating a time-series of remotely sensed Landsat satellite imagery. The Tekes River alluvial fan has been subject to human development in three main ways, dam construction, irrigation development, and agriculture expansion. There are four main research objectives in order to document the development and possible impacts the research objectives of this project are:

1. To document dam construction upstream from the Tekes River alluvial fan
2. To document irrigation expansion on the fan
3. To document agricultural expansion on the fan
4. To determine if there has been changes to seasonal variation in NDVI values between the agricultural fields on the fan and natural vegetation

Documenting the expansion of human influence on the unstudied Tekes River alluvial fan will allow for an understanding of how development has occurred over time. Further research could expand upon these findings in order to understand more about the environmental effects the documented human influence has had on the region. But it is first necessary to understand how development has occurred overtime.

CHAPTER 2

Study Area

2.1 Overview

The study area for this project is located in Xinjiang province in China (Figure 2.1). Xinjiang is the most Northwestern part of China, bordering several other countries including Mongolia, Russia, Kazakhstan, Kyrgyzstan, and small amounts of Afghanistan, Pakistan, Tajikistan, and India. The province constitutes more than 16% of the country with an overall size of over 1.6 million km^2 (Wang et al., 2020). Sun et al. (2010) describe Xinjiang as having a unique topography with three paleo-orogens (or mountain belts), and two basins (the Altai Mountains, the Tian Shan Mountains and the Kunlun Mountains; the Junggar Basin and the Tarim Basin). The Tian Shan (also spelled Tien Shan) Mountains make up the Eastern portion of the Central Asian Orogenic Belt which spans more than 2500 km in Central Asia (Wang et al., 2020), and cross parts of Kazakhstan, Kyrgyzstan and China. Typically, mountain-basin systems are sensitive landforms that are highly reactive to global changes in climate (Li et al., 2012). Xinjiang, with a more complex mountainous topography, is susceptible to these changes. The study area is located in the Northwestern region of Xinjiang between the Southern and Northern Tian Shan mountains.

Figure 2.1 A Broad Study Area Map. Highlighting Xinjiang Province in green and the relevant rivers and the location of the Tekes River Alluvial Fan.

The current climate in Xinjiang is categorized as arid to semi-arid (Wang et al., 2020), with an annual temperature range of -20 to 30 °C (Han et al., 2020). Xinjiang, China receives on average 400mm of annual precipitation (Han et al., 2020), mostly (80%) during April – Sept, and average annual evapotranspiration is 1358mm per year (Zhang et al., 2011). However, Terekhov et al. (2020) states the Tekes River region has a continental climate, blocked by the Tian Shan mountains, resulting in large variation in annual moisture content. The temperature in Xinjiang varies from 7 ^{o}C to 37 ^{o}C year-round (Li et al., 2017). Han et al. (2020) states that Northwestern China is the most underdeveloped region of China with an agriculture-based economy, resulting in Northwestern China having the lowest gross domestic product (GDP) per capita in the country. The semi-arid to arid climatic region with an economy based on agriculture, underlines the importance of freshwater resources. The region is not stable without irrigation (Han et al, 2020). Between 2003 - 2013 the amount of agricultural water use hit its peak in China, with 95% of this used for irrigation. By 2017, the amount of agricultural water use decreased by about 4%, leading Hun et al. (2020) to conclude that China has reached its irrigation water limit.

Wang et al. (2020) exemplifies Northwestern Xinjiang's sensitivity to climate by explaining that it has been transitioning from a warm-dry to a warmer-wet climate since the mid-1980s as a result of global climate change. Li et al. (2012) supports this by explaining this region has seen an increase in temperature by approximately 0.34 °C per decade from 1960 to 2010, and there has been an increase in annual precipitation of about 3.7% per decade from 1961 to 2015 (Wu et al., 2019). However, Wang et al. (2020) discusses that this increase in precipitation is not sufficient to alter the nature of the semi-arid to arid climate in Xinjiang. The increase in annual precipitation is mainly due to a few instances of severe rainfall events, primarily in the Tian Shan Mountain region (Wu et al., 2019), which will likely affect the landforms below, such as the Tekes River.

2.2 Tekes River

The Tekes River is a first order river originating in the Tian Shan Mountains and travelling for 200 km in Xinjiang before forming the Tekes River alluvial fan. The Tian Shan Mountains crosses the boundary of Kyrgyzstan, Kazakhstan and China; there are two portions of the Tian Shan Mountains which are located in China (Figure 2.2), known as North and South Chinese Tian Shan

Mountains. The Tekes River is a primary river, fed by precipitation and glacier melt water from its upper catchment area, the southern Tian Shan Mountains, from an elevation of approximately 5280 m (Figure 2.2). The Kash River merges with the Tekes River, 150 km downstream, the Tekes River continues for approximately another 50 km before the apex. The fan terminates into the Kunes River which later turns into the Ili River which travels for approximately 770 km and crosses the broader into Kazakhstan before terminating in Lake Balkhash (Figure 2.2).

2.3 Tekes River Alluvial Fan

The Tekes River alluvial fan (43° 30' 28" N, 82° 29' 46" E) is 18 km long from apex to the toe with a change in elevation of 70 m, resulting in a very gradual slope of 0.2°. Figure 2.3 shows a map of the Tekes River alluvial fan on a (a) topographic hillshade map and (b) on a satellite image to show the appearance of the surrounding valley. The blue channels show the active fan channels which were identified using the satellite image. The yellow cone-shaped polygon represents the estimated total area of the alluvial which includes the inactive areas. The active area on the Tekes River alluvial fan encompasses approximately 160 km^2 however, the entire fan surface, shown in yellow, measures roughly 350 km^2.

Fontana et al. (2014) categorizes this fan as a fluvially dominated, due to its length (greater than 10s of km in length) and is therefore dominated by common fluvial processes of large rivers such as avulsions. On fluvial dominated fans, avulsions may be the most important controlling factor in fan evolution (Fontana et al., 2014). Furthermore, fluvial dominated fans will typically have higher amounts of river sediment deposition near the terminal end of the fan as water either infiltrates or evaporates by this point (Fontana et al., 2014). The active area of an alluvial fan is the area that is still subject to flow, transport, and deposit sediment.

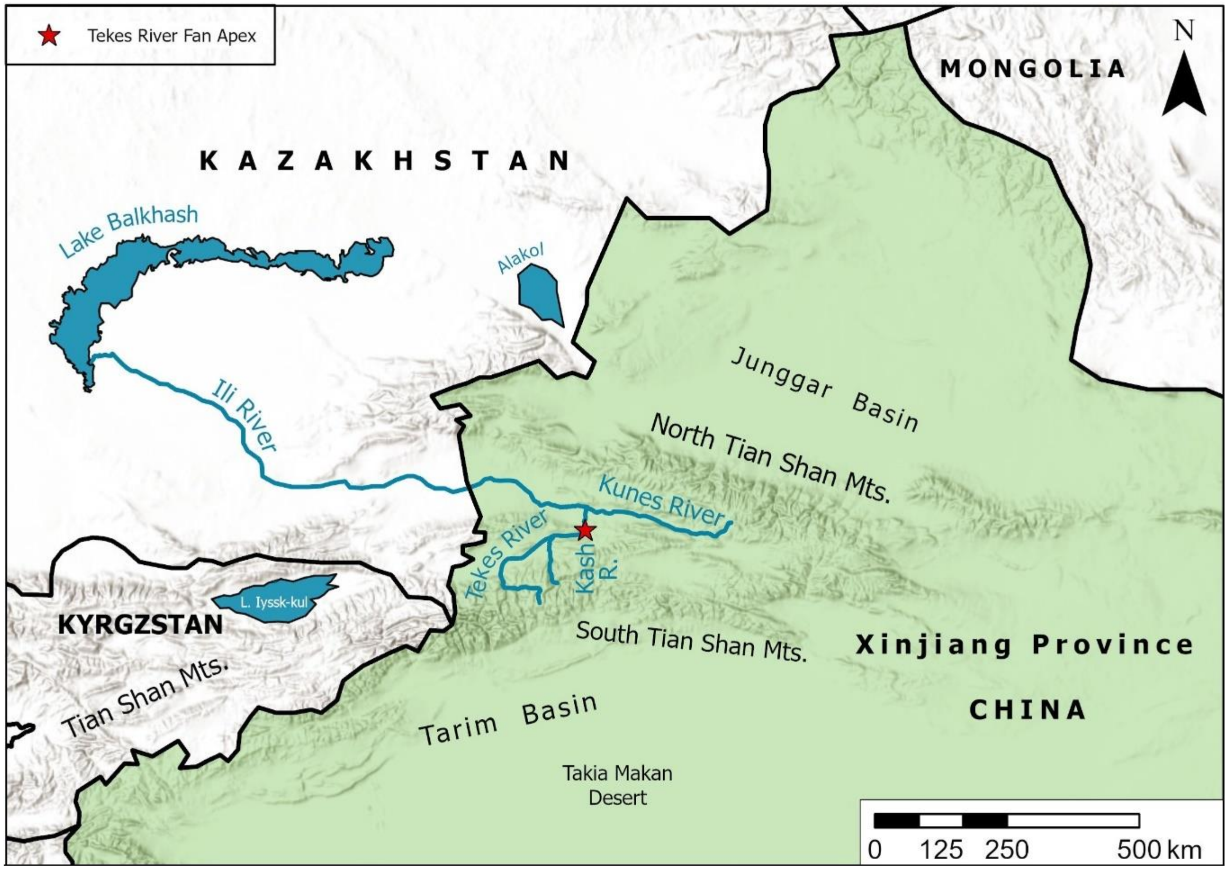


Figure 2.2 A regional Study Area Map. Showing the relevant geographic characteristics of the study area.

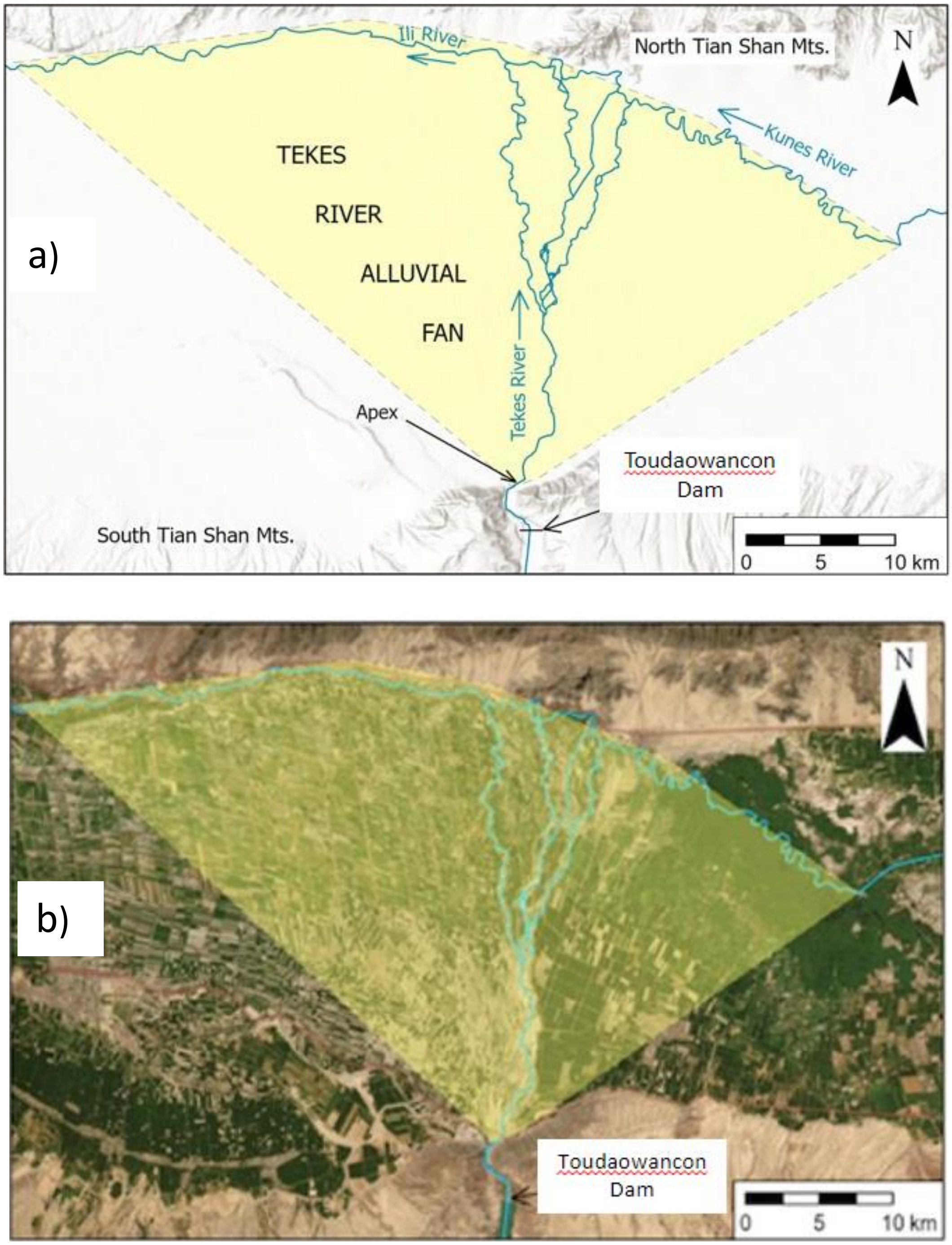


Figure 2.3 Map of the Tekes River alluvial fan. a) the fan mapped in ArcGIS b) fan mapped on satellite image to show surrounding landscape

2.4 Anthropogenic Development

The Tekes River has been subject to four hydropower dams in recent years. Three of those dams are constructed on the Tekes River and the fourth is located on the Kash River. With the use of satellite imagery, extensive agricultural development can be seen along the entire length of the Tekes River's banks and valley. Confining rocky-mountainous terrain seen along much of the Tekes River valley, which is unsuitable for agriculture, but agriculture can be seen dominating any possible low-lying areas throughout the valley. Agricultural development mainly is seen on the non-active surfaces of the fan, but some agriculture can even be seen in between the channel networks in the active zone of the fan.

CHAPTER 3

Methods

3.1 Landsat Image Dataset

A 31-year time-series of 30-m resolution Landsat images was constructed from free downloaded imagery from the U.S.G.S. Earth Explorer website; the study area was located on satellite path 146 and row 030. Historical data was available for the Landsat 5, 7 and 8 satellites dating back to 1990 up to 2021. Initially, the search was limited to summer months (June, July, August) and cloud clover of 10% or less. The reason for the temporal limit was to avoid using images with snow cover on the fan. However, to create a dataset with one image per year from 1990 to 2021, some images were selected from the months of outside of the summer. Once appropriate images were found, spectral bands 1 – 5 and 7 were downloaded from the U.S.G.S. website. Due to limitations of the imagery available, 27 images made up the 31-year time series, shown in Table 1, with years 1993, 1995, 2004, 2005, and 2012 missing.

Table 3.1 The Complete Dataset of Landsat Images.
For reference, L5 denotes Landsat satellite 5 was used.

Year	Date	Landsat
1990	August 2, 2022	L5
1991	November 1, 2022	L5
1992	June 4, 2022	L5
1994	August 29, 2022	L5
1996	May 14, 2022	L5
1997	August 21, 2022	L5
1998	September 25, 2022	L5
1999	September 4, 2022	L7
2000	August 5, 2022	L7
2001	August 8, 2022	L7
2002	July 26, 2022	L7
2003	May 26, 2022	L7
2006	August 16, 2022	L5
2007	August 17, 2022	L5
2008	July 2, 2022	L5
2009	July 21, 2022	L5
2010	July 24, 2022	L5
2011	June 25, 2022	L5
2013	August 1, 2022	L8
2014	July 19, 2022	L8
2015	July 22, 2022	L8
2016	August 9, 2022	L8
2017	August 25, 2022	L8
2018	August 15, 2022	L8
2019	July 17, 2022	L8
2020	June 1, 2022	L8
2021	August 23, 2022	L8

Two primary software were used to carry out the objectives of this research: Geomatica PCI and ArcGIS Pro. Geomatica PCI was used for remote sensing purposes and ArcGIS was used to carry out mapping and exporting Landsat Images. To compile the individual bands into a single viewable image, the six bands were imported and saved as .PIX files in Geomatica PCI. The original Landsat image files captured a much larger surrounding area than the extent of the study area. As a result, each image was clipped three times to remove unneeded imagery and allow for accelerated processing time. The first and second clips were used to map the overall study area and determine the location of dams. The third level of clipping encompassed the extent of the alluvial fan and terminal river; therefore, these images were used most widely throughout the project to focus on the specific study area.

3.2 Documentation of Dam Construction

The date of construction of the four dams upstream from the Tekes River alluvial fan was determined using a combination of software, including Google Earth Pro and Geomatica PCI. The historical function in Google Earth Pro allowed for the location and determination of the approximate date that each dam was constructed. From this, the dams were located on the largest clipped image nearest to the date before and after dam construction. These images were then clipped to include only the extent of the dam on the river and the resulting reservoir. The clipped images were imported into ArcGIS Pro and the surface area of the reservoirs were measured using the software’s Measuring Tool. The images were then mapped to show the expansion of the reservoirs before and after dam construction took place.

3.3 Irrigation Expansion Mapping

To document the irrigation canal development, six years were chosen over the 31-year time series: 1990, 1996, 2006, 2011, and 2021. In order to identify the irrigation canals from the surrounding landscape, an unsupervised classification was used in Geomatica PCI to group/cluster pixels with a similar remote sensing value. The unsupervised classification was applied to a bitmap which encompassed the total fan area and not the entire clipped Landsat image. The unsupervised classification requires three input bands and defined number of classes for which the pixels will be clustered into. The input band combination and number of classes used were chosen uniquely for each image. The proper number of classes and input bands allowed for the irrigation canals to be clustered into one group and appear as one colour distinct from the surrounding vegetation. Afterwards, the result of the unsupervised classification, the georeferenced band, and the fan area bitmap were exported from Geomatica PCI and imported to ArcGIS. In ArcGIS, a new polyline feature class was created to represent the irrigation canals for that year. The canals were mapped by tracing the results of the unsupervised classification, therefore, length data was obtained. Once all the canals were mapped, the unsupervised classification was removed from the map. This process was completed for each of the six images.

3.4 Agriculture Expansion Mapping

Agricultural field development was mapped over time using the same six dates which were used in the irrigation expansion methods. The fields were mapped using a visual assessment of

Landsat imagery in ArcGIS. Beginning with 1990, the agricultural fields were identified and then overlaid with a new polygon feature class in ArcGIS. This layer was added to the next image in the series and new agricultural fields were mapped using a different polygon feature class. This created a map of successive polygons which represented the development and expansion of agriculture in the area.

3.5 Changes to Seasonal Variation in NDVI

To determine if the irrigation and agricultural development has affected the natural seasonal health cycles of the vegetation, the average NDVI values in 2021 of natural vegetation and agricultural fields on the fan were compared. Because natural vegetation on the fan is limited, natural vegetation needed to be tested outside of the fan surface. Therefore, seasonal variation of NDVI was tested in three different sites: agricultural fields on the fan surface, natural vegetation on the fan surface, and natural vegetation near the fan surface. There were six test locations for the agricultural fields, three test locations for the natural vegetation on the fan surface, and three test locations for the natural vegetation near the fan.

In order to obtain seasonal imagery, new monthly 2021 images were downloaded from U.S.G.S. Earth Explorer. Based on the availability and quality of the imagery, seven images were downloaded over six months between April – December in 2021. These images were then clipped in Geomatica PCI to encompass only the required area. In Geomatica PCI, six bitmaps were created in the size of the existing agricultural fields spread out on the fan surface. Three bitmaps of similar size were created on an area of the fan surface which showed natural vegetation cover and an additional three bitmaps were created on an area of natural vegetation cover near but not on the fan surface. The bitmaps were used to delineate the NDVI calculation to that area only. The bitmaps were exported to each of the seven 2021 images in order to calculate NDVI at all the test sites in all the images. The raster calculator function in Geomatica PCI was used to calculate NDVI for each of the three different bitmap sections using Equation 1:

$$\text{NDVI} = (\text{NIR band} - \text{Red band}) / (\text{NIR band} + \text{Red Band}) \qquad \text{(Eq. 1)}$$

where *NIR band* and *Red band* are the digital number values in the near-infrared and red bands, respectively.

All the images used to investigate this objective were sourced from Landsat 8 imagery. Therefore, the raster calculation was the same for each, which used Band 5 as the NIR band and Band 4 as the red band. The raster calculation used a 32-bit real channel type and was masked with the appropriate bitmap so that the calculation only included this area. The average NDVI value of the six or three bitmaps was recorded for each of the test locations and then graphed using Microsoft Excel.

CHAPTER 4

Results

4.1 Dam Construction Time Series

Four dams were built over nine years upstream from the Tekes River alluvial fan beginning in 2005 and ending in 2014. Landsat imagery maps shown in Figure 4.1.1 to 4.1.4, illustrate the effect dam construction has had on the natural rivers' flow regime. In all four cases, the natural river channel appeared narrow and sometimes confined before dam construction took place. Reservoirs of varying sizes had formed behind each dam, with the largest forming behind the first dam, the Kapchagaysky Dam (Table 4.1) which is approximately 14 km Tekes River alluvial fan apex. After dam construction, the reservoir appeared to fill-in most of the low-lying river valley.

Table 4.1 Documentation of showing the construction date and size of the four reservoirs that are upstream from the Tekes River alluvial fan.

	Kapchagaysky Dam	**Toudaowancon Dam**	**Kaxiajia'erxiang Dam**	**Kuokesuxiang Dam**
Year of Construction	2005	2009	2012	2014
Size of Reseroir (km^2)	104.3	12.8	6.5	7.4
Location	43°18'11"N 82°29'11"E	43°23'40"N 82°29'11"E	43°06'34"N 81°53'19"E	43°06'38"N 81°53'18"E

The Toudaowancon Dam, shown in Figure 4.2, is spatially the closest to the fan, approximately 2.50 from the apex. The Toudaowancon reservoir was not fully filled-in by the time the 2008 Landsat image was captured, therefore two images are used to show the progression. The Kaxiajia'erxiang Dam is the furthest upstream from the fan, approximately 130 km, and resulted in the reservoir with the smallest surface area. Finally, the Kuokesuxiang Dam is constructed on the Kash River, approximately 14 km before terminating into the Tekes and approximately 140 km from the fan apex.

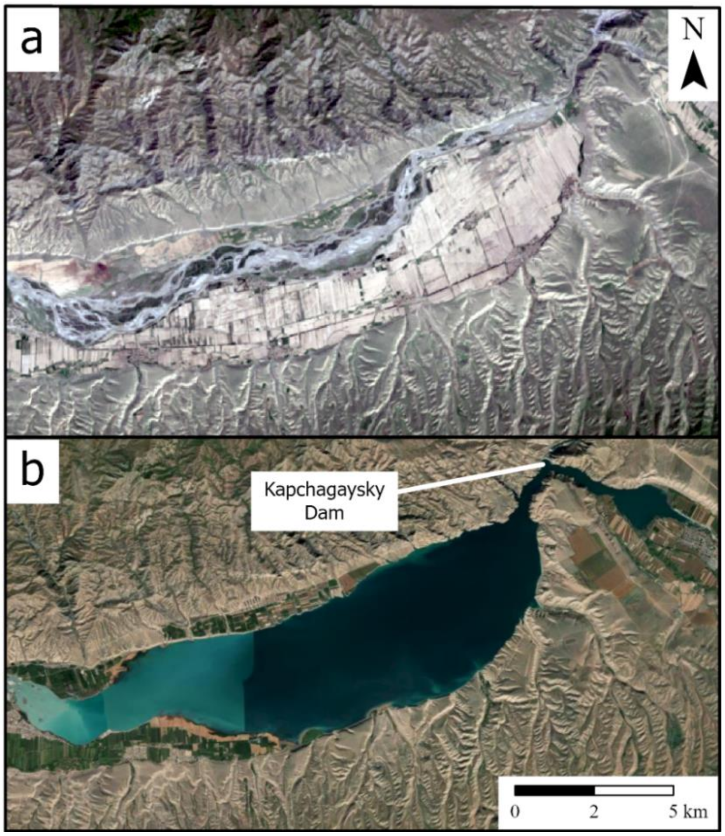


Figure 4.1. Imagery from Landsat showing the Kapchagaysky Dam with natural coloring: A) the Tekes River valley and flood plain in 2003, and B) the Tekes River and Kapchagaysky Reservoir in 2006.

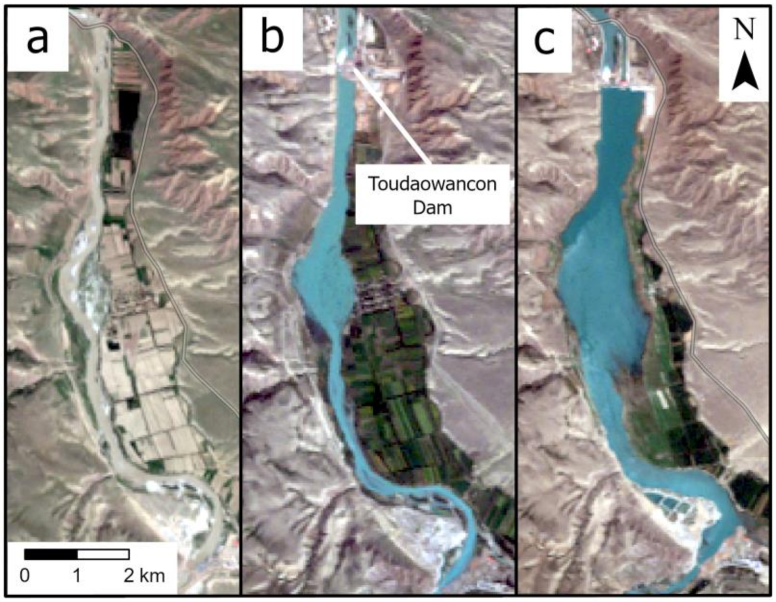


Figure 4.2 Imagery from Landsat showing the Toudaowancon Dam with natural colouring. a). the Tekes River and floodplain in 2008 and b) the Tekes River in 2009 with reservoir partially filled and c) the Tekes River in 2010 with the Toudaowancon reservoir fully filled.

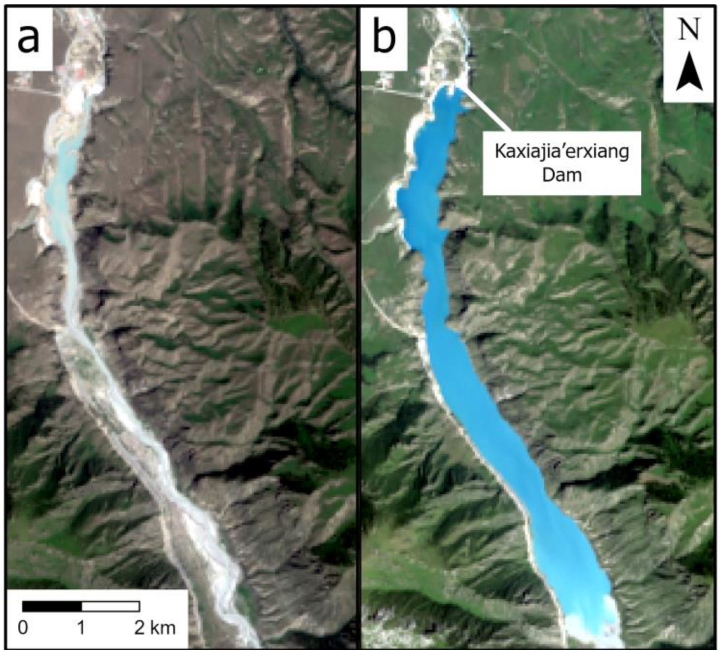


Figure 4.3 Imagery from Landsat image showing the Kaxiajia’erxiang Dam with natural colour a) the Tekes River in 2011 before dam construction b) the Tekes River and Kaxiajia’erxiang Reservoir in 2013 after dam construction.

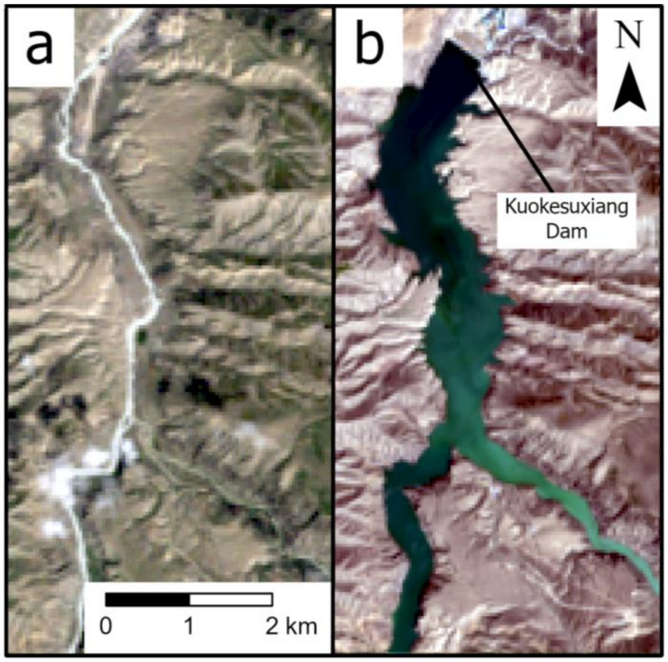


Figure 4.4 Imagery from Landsat image showing the Tuokeum Dam with natural colour a) the Tekes River in 2013 before dam construction b) the Tekes River and the Toukeum Reservoir in 2014 after dam construction.

4.2 Irrigation Development and Expansion

Over the six time periods between 1990 to 2021, the amount of irrigation canals on the Tekes River alluvial fan had increased in a near linear trend (Figure 4.2). Before 1990, there were approximately 109 km of irrigation canals present on the fan surface. As shown in Figure 4.2.2, in 1990, the irrigation canals were primarily situated on the west side of the fan channels. Here, the irrigation canals had a more distinct irrigation pattern, whereas on the east side, the canals showed a less connected network pattern. Early in the time series, the irrigation canals were more proximal on the fan surface. Overtime, especially on the west side of the fan channels, the irrigation canals developed mainly by extending distally towards the terminal river.

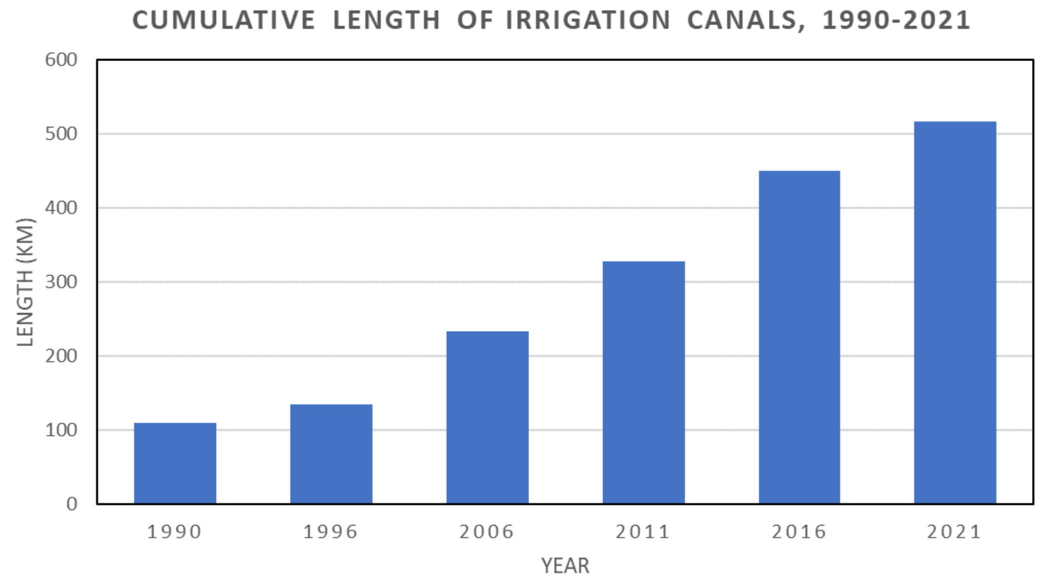


Figure 4.5 Cumulative expansion of irrigation development overtime

The development of long parallel canals that appeared to reach the terminal river was most apparent in 2006 (Figure 4.6). After 2006, development in-filled in the space between the extending canals especially on the west side, which created a denser irrigation canal network shown in 2011 and 2021. On the east side of the fan, growth continued in a more commonly recognizable irrigation canal pattern network. Most development that occurred on the east was seen in 2011. Figure 4.6 shows that this development occurred in the distal part of the fan.

The period between 1990 and 1996 showed the least amount of irrigation canal development with only an additional 25 km. The longest duration next period occurred over ten years (1996 – 2006), for which the irrigation canals increased by 99 km. The following period occurred over five years (2006 – 2011) for which 95 km of new canals were constructed. The largest increase in canals of 122 km occurred over the next period (2011 – 2016) shown in Figure 4.6 Much of this took place on the west side of the fan channels in a filling-in pattern in addition to distally extending canals. The 2016 – 2021 period accounted for the second least amount of canal development (67 km). The total length of the irrigation canals on the fan surface increased from approximately 109 km in 1990 to approximately 517 km by 2021.

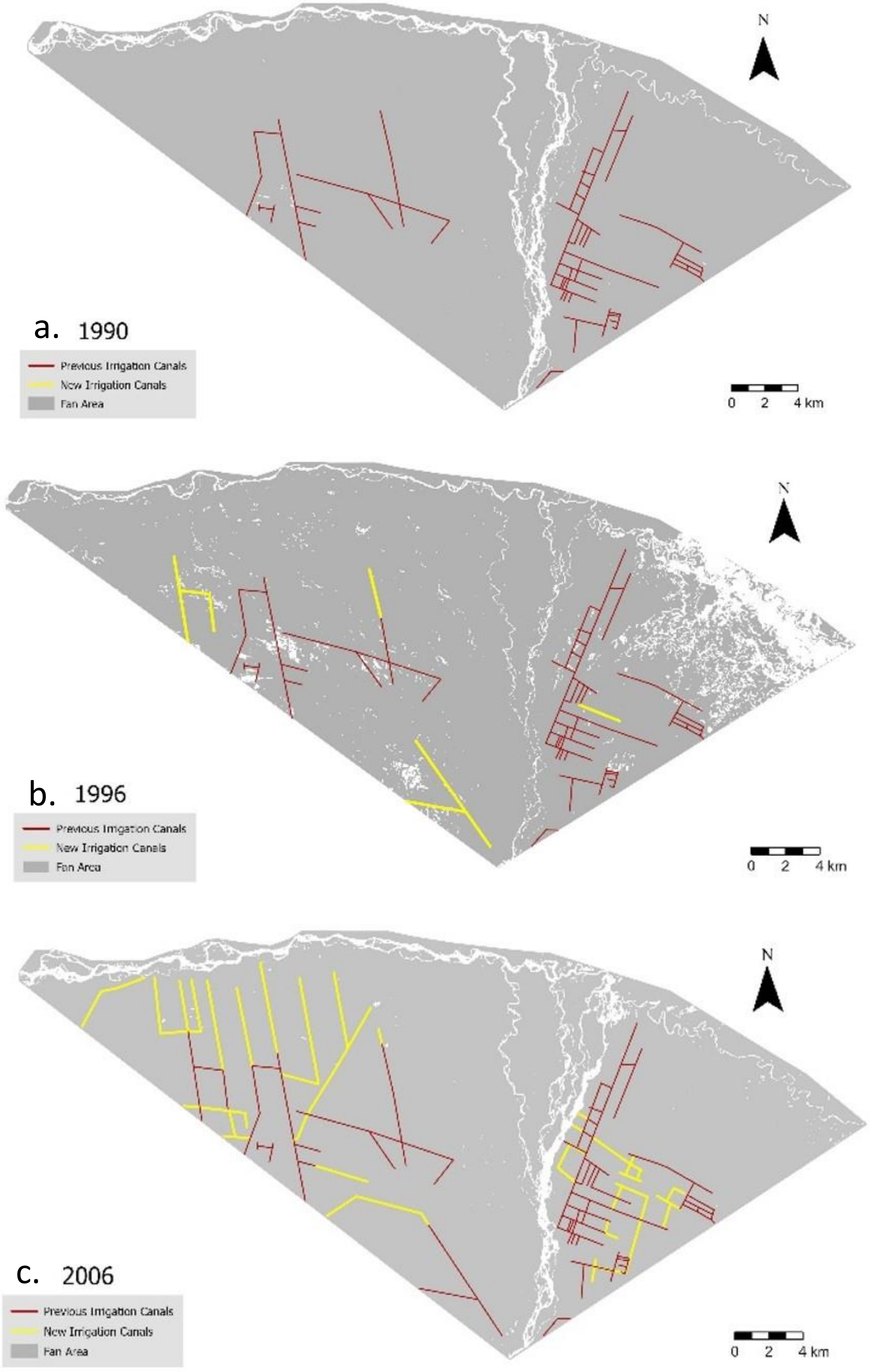


Figure 4.6 Illustration of the irrigation development on the fan mapped over time

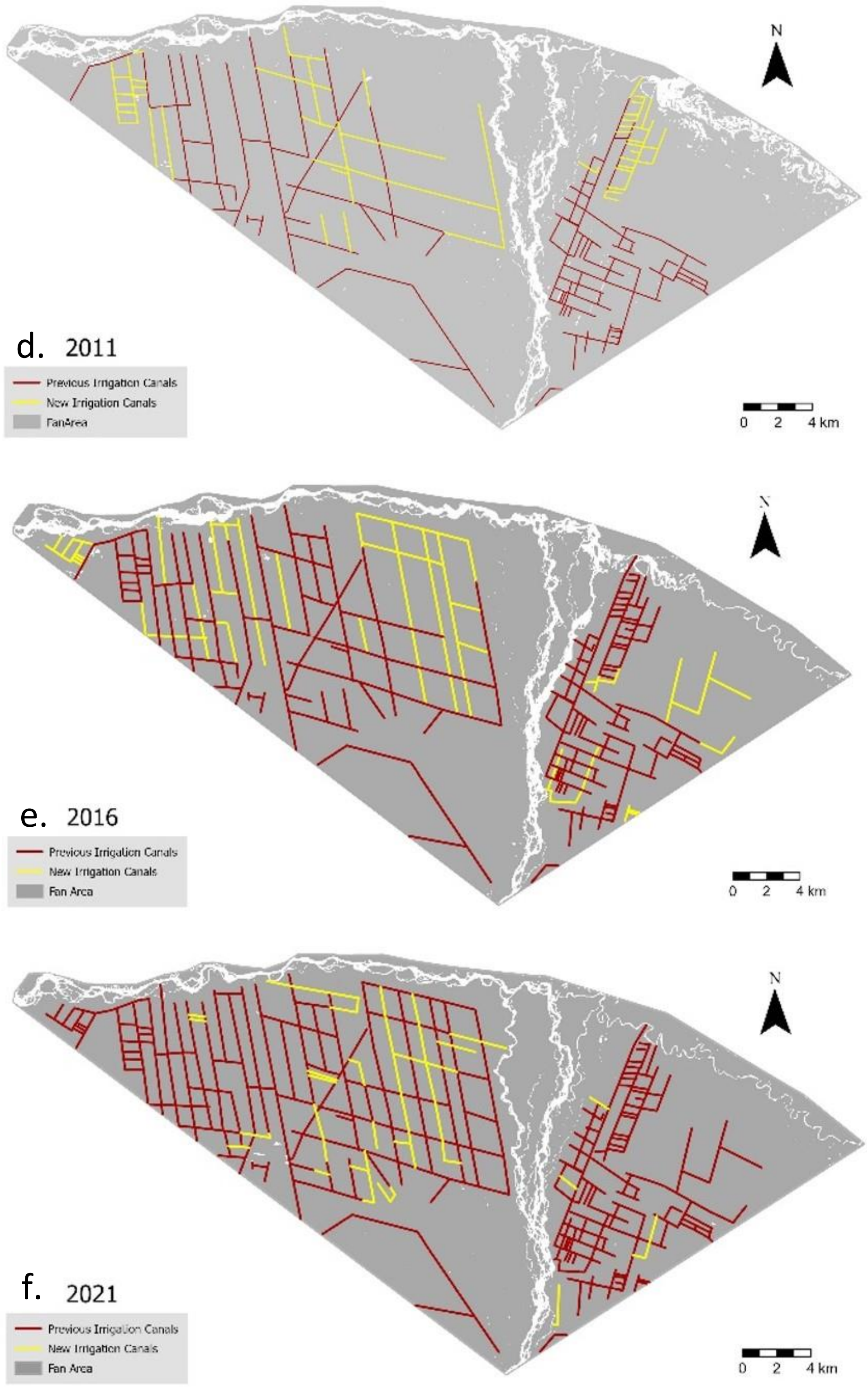


Figure 4.6 (Continued) Illustration of the irrigation development on the fan mapped over time

4.3 Expansion of Agriculture

Over the six time periods between 1990 to 2021, the agricultural fields on the fan surface increased consistently as shown in Figure 4.7. Prior to 1990, approximately 107 km^2 of agricultural fields were present on the fan surface. Slightly more than half of these fields were found on the east side of the fan channels (Figure 4.8 a.). The second time period (1990 – 1996) resulted in the least amount of agricultural development (5 km^2) in the time series. Between 1996 and 2006 the second largest (66 km^2) amount of agriculture fields was developed. As seen in Figure 4.8 c., this mainly occurred on the west side of the fan channels.

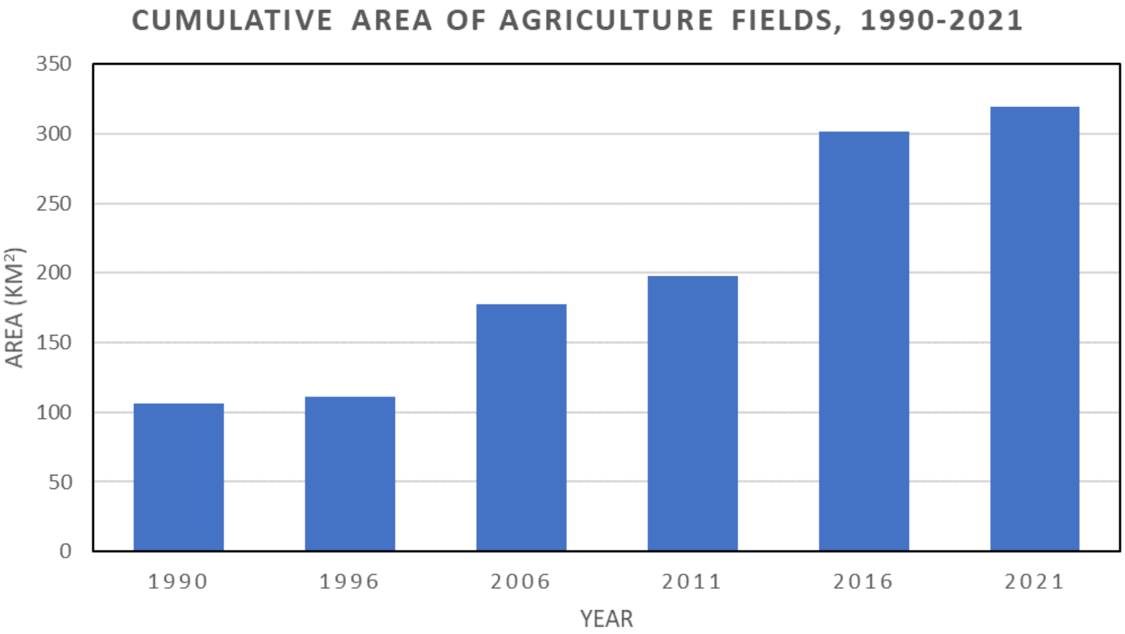
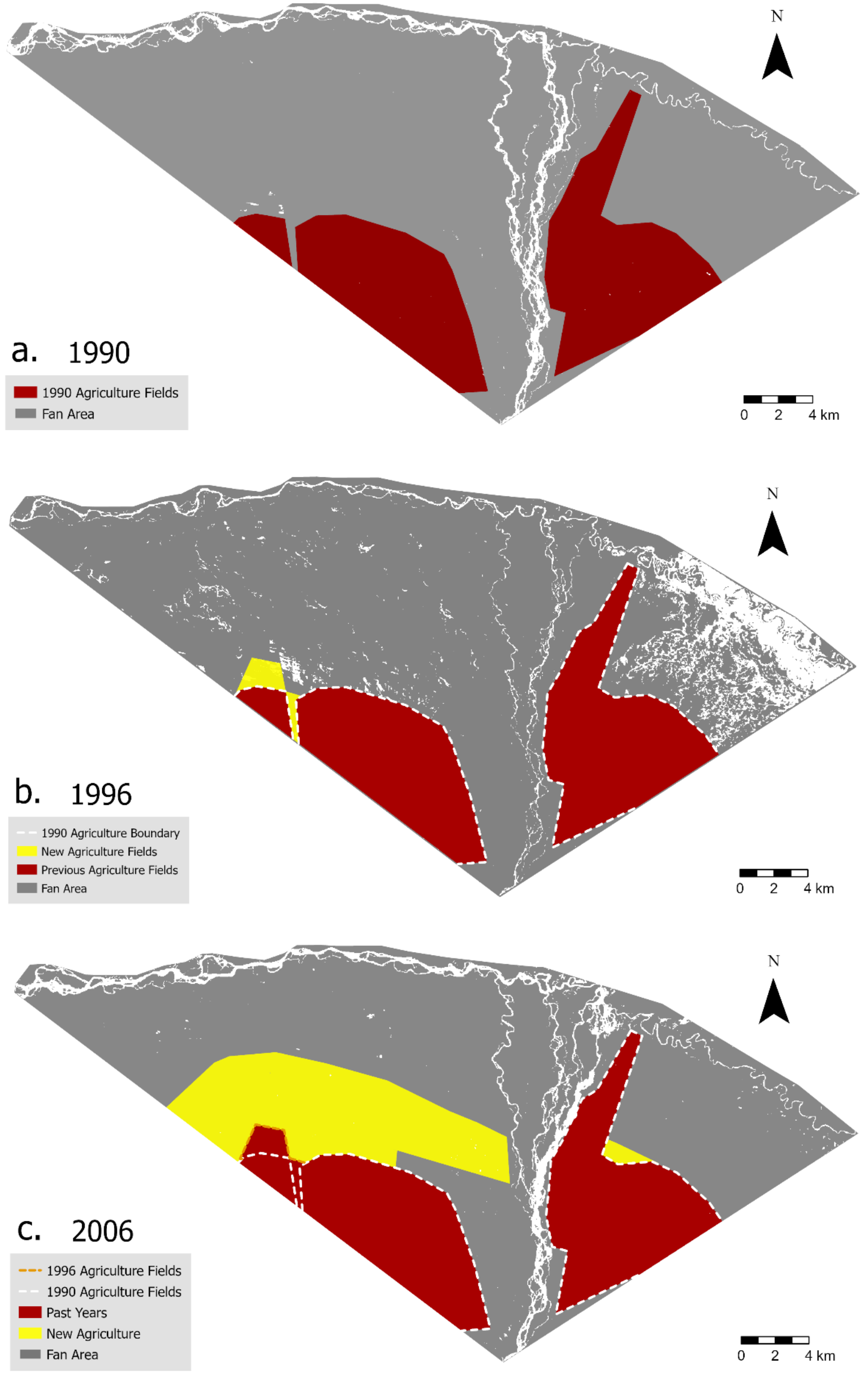


Figure 4.3 Cumulative expansion of agricultural field development overtime

There was a moderate increase in agricultural development in the fourth time period from 2006 to 2011 of 20 km^2 (Figure 4.8 d). The fifth time period between 2011 and 2016 had the most development of agricultural fields amongst the time series, which mainly occurred on the west side of the fan as shown in Figure 4.8 e. On the east side of the fan, two sections of agricultural fields developed in between existing agriculture and the fan channels. An additional relatively small section of agricultural fields was identified on the eastern side above 2011 and 2016 agriculture (Figure 4.8 f). Furthermore, it is notable that this period was the first instance agricultural fields appeared in between active fan channels. In the final time period between 2016 and 2021, approximately 18 km^2 of agricultural fields were developed. Based on Figure 4.8 f., the new agricultural fields developed during this period appeared adjacent or near the active fan channels.



4.8 Illustration of the agricultural development on the fan mapped overtime

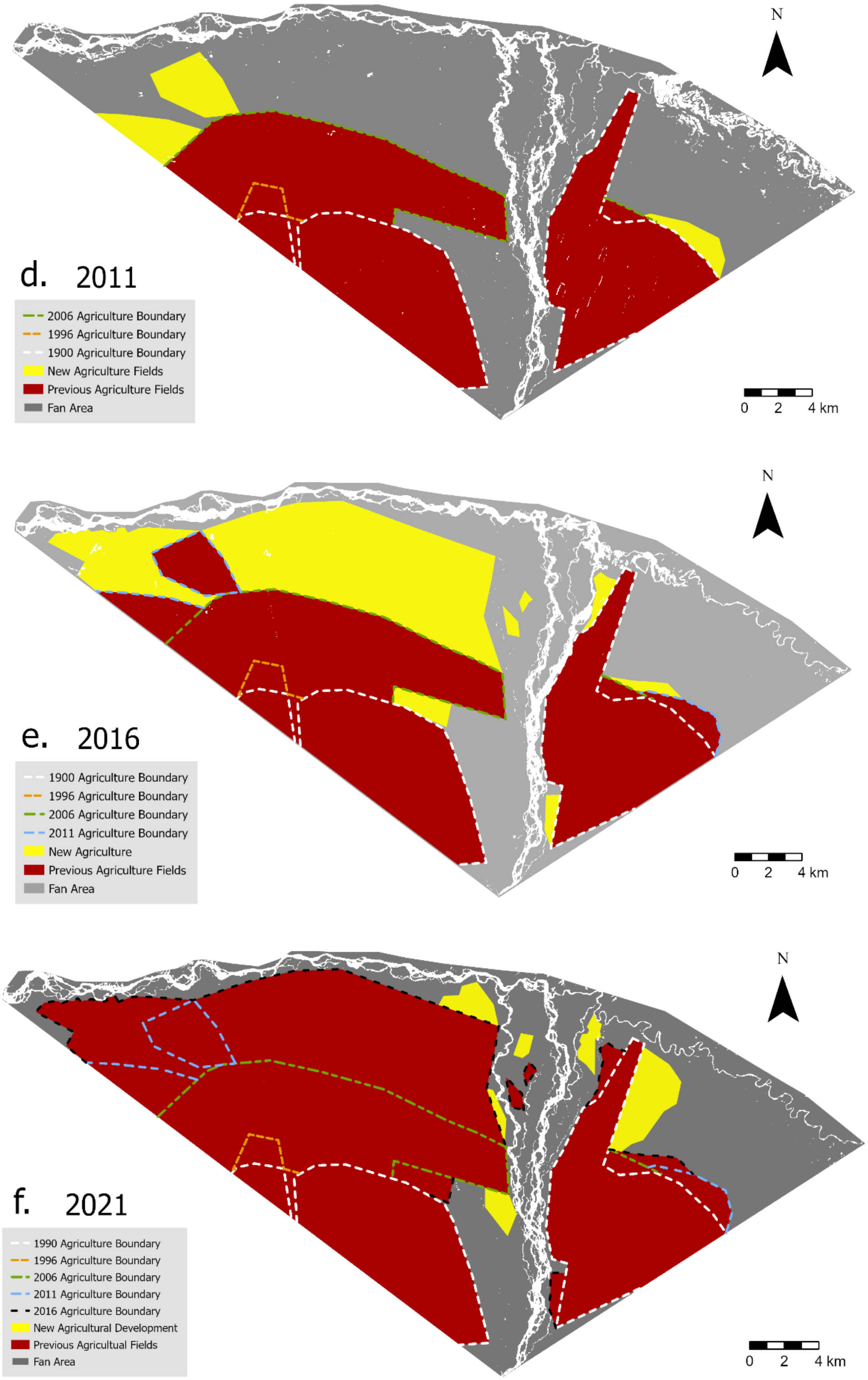


Figure 4.8 (Continued) Illustration of the irrigation development on the fan mapped over time.

4.4 Seasonal Variation in NDVI

The average NDVI value from each of the test sites was retained and plotted on the same line graph over Julian dates shown in Figure 4.9. The first two dates, early March and mid-May show a similar pattern. The average NDVI for the agricultural site on the fan surface was the lowest at approximately 0.11, compared to the average NDVI value of natural vegetation near the fan (0.15) and on the fan (0.17). This pattern appears again on the following date, agricultural fields produced the lowest average NDVI (0.25), followed by natural vegetation near the fan (0.30), then on the fan (0.34) which produced the highest NDVI value. Within the third period, Julian date 219, the agricultural sites and natural sites on the fan produced similar average NDVI values (0.39 and 0.40 respectively). Compared to natural vegetation near the fan, the value produced the lowest average NDVI of approximately 0.33. The average NDVI of the

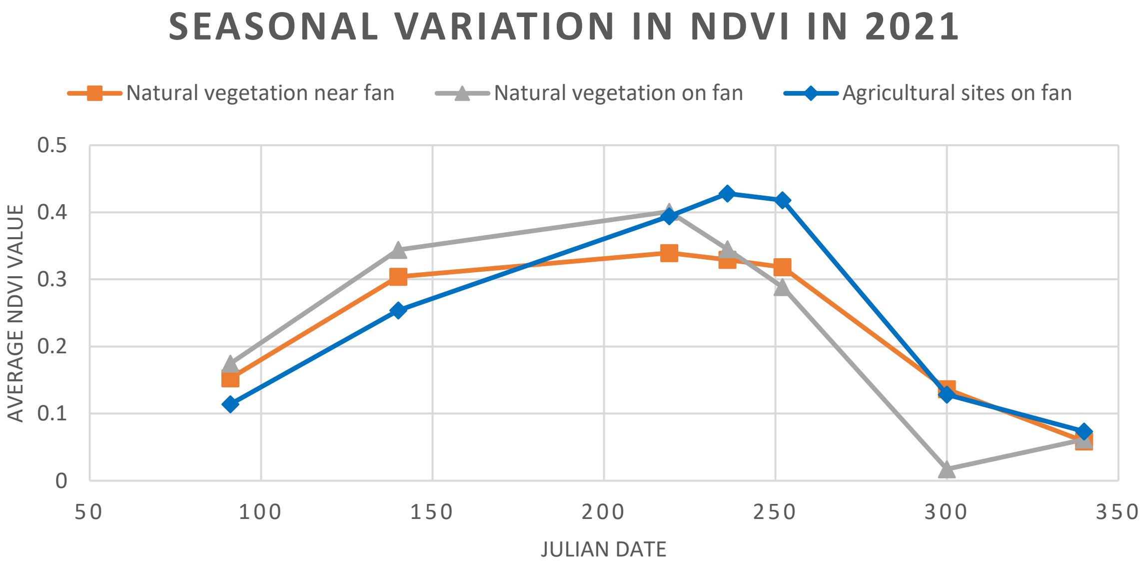


Figure 4.9 Seasonal variation in NDVI. For reference, Julian dates 100 and 250 are April 10 and September 7, respectively.

agriculture sites on the next date (Julian date 252) continued to increase, resulting in the largest value (0.42) compared to the other two sites. This was the date that the average NDVI on the agricultural site peaked. As well, the natural vegetation site on fan decreased sharply to approximately 0.29. This was still slightly greater than the average NDVI calculated from the natural vegetation site near the fan. During this time, NDVI near the fan decreased to approximately 0.33.

By the 300th day of the year, the NDVI calculated for natural vegetation on the fan continued to sharply decrease, resulting in the lowest average NDVI (0.017) amongst the sample sets. Conversely, test sites for agricultural sites on the fan, and natural vegetation near the fan produced an NDVI of 0.129 and 0.136 respectively. The last date for which NDVI was tested was on the 340th day of the year. On this date, the average NDVI values for all three test sites produced similar results. Agricultural sites on the fan resulted in a slightly greater average NDVI of 0.073, while natural vegetation on the fan equalled 0.062, and natural vegetation near the fan equalling 0.059. Based on these results, the seasonal NDVI peak on the agricultural field was delayed and slightly higher than that of the natural vegetation test sites.

Overall, the average NDVI values between the three test locations were similar over time in 2021. For the first two dates, the average NDVI for the agricultural fields was the lowest compared to the two natural test locations. Then the agricultural NDVI peaked from mid July to early September, which was the greatest average NDVI between all the test locations by more than 0.1. Furthermore, the peak in seasonal NDVI for the agricultural fields was slightly delayed by approximately two months compared to the natural vegetation.

CHAPTER 5

Discussion

5.1 Dam Construction

The purpose of dam construction on a river is to alter downstream hydrology to provide various functionality including reduced floods, increased low flow periods, alter the timing of peak and low flow levels, as well as generate hydropower in some cases (Graf, 2006). Downstream effects such as these became observed immediately upon construction, but other by-product changes may take longer to become obvious as, such as sediment accumulation. Dams act as effective sediment traps results in a decrease in sediment transport and load downstream (Williams et al., 1984). For example, Williams et al. (1984) studied the Glen Canyon Dam on the Colorado River in the United States and found there was an 87% reduction in suspended sediment between pre (1926 – 1962) and post (1963 – 72) dam. Interestingly, the measuring station on the Colorado River was 180 km downstream from the dam (Williams et al., 1984). This is a much larger distance than the Tekes River. Therefore, it can be inferred that the four dams upstream from the Tekes River alluvial fan have caused or will cause a reduction in sediment supply on the fan. However, the William et al. (1984) study considered 46 years in total, while the dam construction on the Tekes River over a 16-year timeframe 2005 - 2014. It is possible that within the time period of this study, the dams have not been in place long enough for there to be a drastic decrease in sediment supply on the fan surface but there likely will in the future. This reduction in sediment yield often persists even if the dams were to be removed (Williams et al., 1984) therefore, the Tekes River and alluvial fan has likely been altered indefinitely as a result of dam construction.

Reduction in sediment transport in rivers as a result of dams increases erosion and incision in the river channel downstream from the dam (Graf, 2006; Taylor, 1978). Flow leaving the dam is relatively sediment free and capable of downcutting, leaving the remaining bed of the channel consisting of coarser grain sizes compared to before the dam was constructed (Graf, 2006; Williams et al., 1984). Williams et al. (1984) found that this down-cutting effect can extend for up to hundreds of km downstream from the dam. Depending on discharge rates of the Tekes and tributary rivers as well as the size and purpose of the dams, it is possible that the Tekes River alluvial fan experienced the erosion and downcutting effects of the dams. Furthermore, due to a reduction in sediment, Nichols et al. (2019) found that this promoted further regrading of sediment on the fan surface as dams have been found to cause a greater range in grain sizes because distal parts of the contain finer grain sizes than before the dam. In a natural setting, grain size grades from coarser to finer grain sediment from proximal to distal reaches of the fan.

Furthermore, a study of the effects of low-tech rock check dams on an alluvial fan in Santa Rita Experimental Range in Arizona, USA, revealed that overall, the alluvial fan channels became stabilized (Nichols et al., 2019). Therefore, the amount of avulsions decreases and areas of bare soil stabilize, called interfluves, and vegetation was able to grow (Nichols et al., 2019). This could explain why agricultural fields appear within the active fan channels observed in 2016 and 2021. However, the Nichols et al. (2019) study observed vegetation growth on interfluves after a 10-year period. The number of agricultural fields within the active fan channels could increase as confidence that avulsions will not affect the fields increases due to the channel stabilization that the upstream dams provide.

5.2 Effect of Irrigation

Irrigation allows for controlled timing of the release of water to crops, which can greatly improve the efficiency of crop yields (Liu et al., 2012). Irrigation relies on water sources from nearby rivers or by sourcing groundwater through well pumping which can have a great effect on the natural water cycle in the area (Liu et al., 2012). Water demands, driven by population increase and industrial development has led to an expansion of irrigation on the Tekes River alluvial fan. Irrigation collects and stores surface water and precipitation, which can lead to decreased infiltration rates and decreased groundwater recharge rates (Shoa et al., 2009). Further, some irrigation practices require groundwater pumping which can lead to overexploitation of groundwater resources resulting in water-shortages and poor water quality (Liu et al., 2012; van Oort et al., 2015; Shoa et al., 2009).

Liu et al. (2012) studied the consequence of irrigation development on an alluvial fan in the Gurbantünggüt Desert in North Xinjiang (approximately 550 km from Tekes River alluvial fan). This area experiences a similar climate and precipitation patterns as the Tekes region.

Furthermore, a rapidly increasing population, increasing need for agriculture, and minimal suitable agricultural land has resulted in an increase in irrigation and crop development on the Gurbantünggüt Desert alluvial fan (Liu et al., 2012). The impact of irrigation in North Xinjiang was estimated to have caused a gradual decrease in groundwater levels from 1992 – 2007 by 0.3681m (Liu et al., 2012). Research assessed whether irrigation had caused a difference in the spatial distribution of the groundwater in the area and found very slight alterations to the concentration of groundwater, resulting from groundwater pumping (Liu et al., 2012).

A similar study by Li et al. (2007) focused on the groundwater quality and quantity in the Yellow River Alluvial Fan region in Xinxiang, Northeastern China before and after vast amounts of irrigation developed on the fan. Although roughly 2,000 km away from the Tekes River alluvial fan, the Yellow River Alluvial Fan is subject to a similar climate, precipitation pattern and has similar fan characteristics such as a very gradual slope (Li et al., 2007). The results from this study found that there was a significant decrease in the vertical position of the water table by 12 m from 1974 – 2005 due to irrigation practices (Li et al., 2007).

The results from the previously described studies demonstrated declines in the position of the water table and quality of the water table as a result of irrigation development. Based on the available information about the agricultural practices on the Tekes River alluvial fan, it is not possible to understand the specific irrigation implications on the fan. However, based on the results of the irrigation expansion objective, it is clear that the Tekes River alluvial fan has experienced great development in irrigation. Based on the agricultural practices in surrounding areas around Tekes, it is likely that the groundwater systems are experiencing similar declines such as what has been found on the Yellow River alluvial fan and the alluvial fan in the Gurbantünggüt Desert. However, more information about the irrigation practises on the Tekes River alluvial fan is required such as, the water release scheduling and methodology, and how reliant the irrigation is on groundwater pumping (Shao et al., 2009).

5.3 Impacts of Agricultural Development

Agriculture is important for the Xinjiang economy but is heavily influenced by droughts (Zhang et al., 2014; Zhang et al., 2018). For example, Zhang et al. (2014) observed that the most recent drought occurred in 2000 – 2007. But Zhang et al. (2014) also found that there has been an increase in precipitation in the province which has decreased the hazard of droughts. However, the high evapotranspiration rate in the area greatly exceeds the increased rate of precipitation; therefore, the increased rate of precipitation is not sufficient to counteract the hazard of drought (Zhang et al., 2018).

The industrial crop cover and crop water usage or crop water footprint (CWF) in the province was analyzed by Zhang et al. (2018). In 1988, the most widely planted crop in Xinjiang was wheat, followed by corn, then cotton (Zhang et al., 2018). By 2015 the planting structure changed such that the crop planted the most was cotton, then wheat, followed by corn (Zhang et al., 2018). This shift in crop cover was explained by Zhang et al. (2018) as due to the political guidance and emphasis on the cotton crop production. Cotton production in all of China has grown but growth has been the largest in Northwestern Xinjiang (Feng et al., 2017).This shift in planting structure has led to an increase of CWF by 256% from 1988 – 2015 because cotton requires approximately 10,000 L of water to produce 1 kg of commercial yield (Zhang et al., 2021). Conversely, wheat and corn are considered low-water-consumption crops (Zhang et al., 2018).

Overall, several crops have increased in production in Xinjiang Province in recent decades, including, cotton, soybean, jujube, and pear which have increase by 1000% between 1988 and 2015 (Zhang et al., 2018). Moreover, rice, wheat, and oil crops increased by 200 – 400% for the same time period. The type of crop that is planted in Xinjiang is driven by (1) price differences (2) increases in urbanization in the area, and (3) increase in consumption of meat which accelerated the planting scale of feedstock crops (Zhang et al., 2018). Interestingly, Zhang et al. (2018) stated that neither the type of crop nor the overexploitation of groundwater resources have influenced the agriculture or irrigation policies in Xinjiang Province. Some agricultural water conservation projects are in effect, such as the Three Lines Project, but none of these policies have clear targets for water use reduction (Zhang et al., 2018). The increasing demand on agriculture and lack of regulatory policy has allowed farmers to enlarge their planting area rapidly. Their relatively fast planting has often led to disorderly agricultural development (Zhang et al., 2018) which can be seen in the disorganized field patterns. This is true for agriculture seen on the Tekes River alluvial fan as field patterns differ greatly across the fan surface based on field orientation and size.

Although information pertaining to the specific crop cover on the Tekes River alluvial fan is underrepresented in the literature, it can be inferred that the typical agricultural crops in Xinjiang represent the crop patterns in Tekes. Without enforced policies coupled with increased demand of agricultural yields, it appears as though there are no reasons for agricultural or irrigation development to decrease. Increasing agricultural development, reliance on groundwater resources, as well as controlling water flow on the fan through upstream dams could cause a shift in the seasonal health of the crops on the fan surface over time.

5.4 Effects of Irrigated Agricultural Development on NDVI

Alterations to water supply has obvious effects on vegetation health; however, unnatural agricultural fields provide consistent water supply to crops but can also lead to a lowering of the water table. Lv et al. (2013) studied the changes in NDVI as a function of increased depth to water table in Hailiutu River in Northern China. Based on root length, some plant species are very sensitive to lowering of the water table whereas others are relatively insensitive (Lv et al., 2013). Plants with naturally deeper root systems are less sensitive because these roots have a larger capillary zone and are able to access a larger range of groundwater than shallow-rooted plants (Lv et al., 2013). Cotton, wheat, and corn are all classified as shallow root plants, with roots usually not exceeding 1 m in depth (Lv et al., 2013). Therefore, the most heavily harvested crops in Xinjiang (and likely on the Tekes River alluvial fan) are all highly sensitive in lowering of the water table which can be driven by over pumping of groundwater or the storing of surface water/precipitation resources in irrigation practises. This creates a positive feedback loop where irrigation allows for an increase in agricultural production but can lead to an increase in water table depth thereby forcing the crops to be solely reliant on water supply from irrigation. Crops can also receive water from precipitation but in areas, such as the Tekes River region, precipitation patterns can be irregular, and droughts are a relatively common occurrence.

Based on the vast amount of irrigation on the Tekes River alluvial fan (as well as evidence from previous research in similar climatic regions) it is likely that the water table depth in the Tekes region has become lower. If so, vegetation on the fan surface would not be able to access enough groundwater to survive. Therefore, an overall decrease in NDVI values would be expected for agricultural fields in 2021. However, this was not observed in the results of the NDVI calculations in this study. Irrigation has allowed for crops such as cotton and wheat to continue to receive sufficient amounts of water although they are no longer able to access groundwater resources. For this reason, there was not an observable overall decrease in NDVI for agricultural fields on the fan surface compared to natural vegetation cover in the surrounding area.

5.5 Limitations of the Research and Suggestions for Further Research

The NDVI research objective for this project was limited temporally and spatially. Based on the available data, NDVI calculations were constrained to just seven periods dates within 2021. It is possible seasonal NDVI variation differences between natural and agriculture vegetation cover could be observed if a longer time period was considered. Moreover, the observed slight delay in the seasonal peak of NDVI in the agricultural sites could also be a result of the spatial distribution of the test locations on the fan. The six text locations were distributed in the relatively distal to intermediate reaches of the fan. It is possible that this area received slightly better growing conditions during the time of the observed NDVI peak than the natural vegetation NDVI test locations. In order to determine if the observed differences in seasonal NDVI variations are in fact a result irrigation expansion, future research will need to consider a longer time frame, such as a minimum of ten years. As well, research similar to Liu et al. (2012), Li et al. (2007) and Shao et al. (2009) which focused directly on changes to the groundwater levels as an affect of irrigation and agriculture would greatly enhance the understanding of magnitude of the human involvement on the Tekes River alluvial fan.

There are some instances, shown in Figure 4.2.1, where the irrigation canals appear discontinuous from the surrounding irrigation network. It is important to note that Landsat imagery has a resolution of 30 m by 30 m pixels which means that it is possible some of the irrigation canals were not identifiable at this scale.

CHAPTER 6

Conclusions and Recommendations

Human influence on the Tekes River alluvial fan has been documented from 1990 – 2021 using remote sensing techniques. Within the 31-year time series, the fan has been subject to four upstream dams, approximately 400 km of irrigation development and approximately 250km^2 of agricultural field development. Direct effects of these developments were not within scope of this project but documenting the development may allow for comparative research in similar regions.

Dam construction can decrease sediment yield thereby increasing erodibility of the flow causing channel down-cutting and channel stabilization. It is possible that is this has occurred on the Tekes River alluvial fan based on the appearance of agricultural fields within the fan channels. This suggests that the farmers are confident that avulsions will not take, place possibly as a result of down-cutting.

Excessive irrigation practices will likely lead to an increase in groundwater depth due to groundwater pumping and/or retention of precipitation which also decreases the amount of surface water. Common Xinjiang agriculture crops such as cotton and wheat would no longer able to access groundwater and would therefore, become reliant on irrigation and precipitation only. The results of the NDVI research objective demonstrated a slight delay in seasonal NDVI variation on the agricultural fields compared to natural vegetation sites. However, it is not possible to conclude that this is because of irrigated water scheduling or an increase in groundwater depth, due to the temporal and spatial limitations in this dataset. Previous literature has found seasonal variation in NDVI due to agriculture and irrigation in similar regions to Tekes (Lv et al., 2013; Lie et al., 2007); however, these studies considered a minimum time period of ten years.

Further research should continue to document and test NDVI in the future as well as consider measuring groundwater levels. This would build upon this research and provided a greater understanding on the anthropogenic impacts on the fan.

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