Land use/land cover change responses to ecological water conveyance in the lower reaches of Tarim River, China (Postprint)

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Date: 2021-12-30T18:52:05+00:00

Abstract

The Tarim River is the longest inland river in China and is considered as an important river to protect the oasis economy and environment of the Tarim Basin. However, excessive exploitation and over-utilization of natural resources, particularly water resources, have triggered a series of ecological and environmental problems, such as the reduction in the volume of water in the main river, deterioration of water quality, drying up of downstream rivers, degradation of vegetation, and land desertification. In this study, the land use/land cover change (LUCC) responses to ecological water conveyance in the lower reaches of the Tarim River were investigated using ENVI (Environment for Visualizing Images) and GIS (Geographic Information System) data analysis software for the period of 1990–2018. Multi-temporal remote sensing images and ecological water conveyance data from 1990 to 2018 were used. The results indicate that LUCC covered an area of 2644.34 km2 during this period, accounting for 15.79% of the total study area. From 1990 to 2018, wetland, farmland, forestland, and artificial surfaces increased by 533.42 km2 (216.77%), 446.68 km2 (123.66%), 284.55 km2 (5.67%), and 57.51 km2 (217.96%), respectively, whereas areas covered by grassland and other land use/land cover types, such as Gobi, bare soil, and deserts, decreased by 103.34 km2 (14.31%) and 1218.83 km2 (11.75%), respectively. Vegetation area decreased first and then increased, with the order of 2010<2000<1990<2018. LUCC in the overflow and stagnant areas in the lower reaches of the Tarim River was mainly characterized by fragmentation, irregularity, and complexity. By analyzing the LUCC responses to 19 rounds of ecological water conveyance in the lower reaches of the Tarim River from 2000 to the end of 2018, we proposed guidelines for the rational development and utilization of water and soil resources and formulation of strategies for the sustainable development of the lower reaches of the Tarim River. This study

provides scientific guidance for optimal scheduling of water resources in the region.

Full Text

Preamble

Land use/land cover change responses to ecological water conveyance in the lower reaches of Tarim River, China

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Abstract

The Tarim River is the longest inland river in China and plays a crucial role in protecting the oasis economy and environment of the Tarim Basin. However, excessive exploitation and over-utilization of natural resources, particularly water resources, have triggered a series of ecological and environmental problems, including reduced river flow, deteriorating water quality, dried-up downstream channels, vegetation degradation, and land desertification. This study investigated land use/land cover change (LUCC) responses to ecological water conveyance in the lower reaches of the Tarim River using ENVI (Environment for Visualizing Images) and GIS (Geographic Information System) software for the period 1990–2018. Multi-temporal remote sensing images and ecological water conveyance data from 1990 to 2018 were analyzed. The results indicate that LUCC covered an area of 2644.34 km^2 during this period, accounting for 15.79% of the total study area. From 1990 to 2018, wetland, farmland, forestland, and artificial surfaces increased by 533.42 km^2 (216.77%), 446.68 km^2 (123.66%), 284.55 km^2 (5.67%), and 57.51 km^2 (217.96%), respectively. In contrast, grassland and other land use/land cover types such as Gobi, bare soil, and deserts decreased by 103.34 km^2 (14.31%) and 1218.83 km^2 (11.75%), respectively. Vegetation area decreased initially then increased, following the order 2010 $<$ 2000 $<$ 1990 $<$ 2018. LUCC in the overflow and stagnant areas of the lower reaches was characterized by fragmentation, irregularity, and complexity. By analyzing LUCC responses to 19 rounds of ecological water conveyance from 2000 to the end of 2018, we propose guidelines for rational development and utilization of water and soil resources and formulate strategies for sustainable development in the lower reaches. This study provides scientific guidance for optimal water resource scheduling in the region.

Keywords: land use/land cover change (LUCC); remote sensing; land use dynamic index; ecological water conveyance; Tarim River

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Received 2020-10-31; revised 2021-08-18; accepted 2021-08-25

1. Introduction

The Tarim River, located in Xinjiang Uygur Autonomous Region, is China' s longest inland river and exhibits the dual characteristics of rich natural resources and fragile ecosystems. The region is strategically important for the "Silk Road Economic Belt" initiative and contributes to China' s economic and social development (Chen et al., 2020; Zuo et al., 2021). The basin is characterized by an extremely arid environment where most natural processes and human activities are directly or indirectly affected by water shortages (Deng et al., 2017; Chen et al., 2020). The lower reaches of the Tarim River have become a focal point for ecological and environmental research in Northwest China, with issues of ecological restoration and security attracting significant attention from both society and government (Yu et al., 2016; Keram et al., 2019; Zhou et al., 2020).

To restore and protect the downstream ecology, the Chinese government implemented a comprehensive management system for the Tarim River Basin in 2000 (Chen et al., 2004; Ablekim et al., 2016). The development of an intermittent ecological water conveyance project has altered the basin' s ecology and environment, resulting in land use/land cover change (LUCC) (Bao et al., 2017; Wang et al., 2021).

Numerous studies have investigated vegetation, biomass, groundwater, LUCC, and ecological benefit assessment responses to ecological water conveyance in the lower reaches (e.g., Shi et al., 2010; Liu et al., 2014; Bao et al., 2017; Chen et al., 2020). Deng et al. (2016) analyzed and evaluated ecological response benefits of vegetation physiology and restoration after water conveyance by monitoring surface water, groundwater, soil water, and vegetation samples through local investigations. Chen et al. (2004) examined the ecological effects of water conveyance by studying vegetation along ecological sections. Zhu et al. (2019) monitored changes in fractional vegetation coverage (FVC) from 2000 to 2017 using time-series NDVI data from MOD13Q1 and explored vegetation growth and recovery under ecological water conveyance. Liu et al. (2014) studied vegetation restoration from 1999–2010 using Landsat TM/ETM and CBERS/CCD remote sensing images based on soil-adjusted vegetation indices.

LUCC is an important indicator for measuring regional ecological sustainability, and studying LUCC is essential for understanding environmental changes and promoting sustainable development (Hao and Ren, 2009; Schirpke et al., 2012). However, few studies have utilized multi-source remote sensing and long-term time series data to monitor and analyze regional environmental changes and ecological responses.

The ecological water conveyance project in the lower reaches has lasted nearly 20 years. This study monitored and analyzed LUCC and ecological responses based on multi-temporal remote sensing images obtained between 1990 and 2018 (a 29-year period). Specifically, we used ENVI, GIS, and statistical analysis software to examine the spatial distribution and temporal dynamics of LUCC, as well as land use change trends and spatial characteristics under intermittent water conveyance conditions.

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2. Study Area

The lower reaches of the Tarim River, located in southern Xinjiang, refer to the section from Daxihaizi Reservoir to Taitema Lake, spanning approximately 428 km (Sun et al., 2011). Riparian forests form a "green corridor" in this arid region, blocking the connection between the Taklamakan and Kuruktag Deserts (Zhou et al., 2020; Zhang et al., 2021). Influenced by the climate of these two deserts, the lower reaches experience drought with minimal rainfall and snowfall, strong evaporation, and high wind frequency in spring and autumn. The region has a typical northern temperate continental arid desert climate, with annual average temperatures of 10.7-11.5°C, precipitation of 17.4-42.0 mm, and evaporation reaching 2500-3000 mm (Xu et al., 2019; Li et al., 2021). The ecological environment is extremely sensitive and fragile.

Since 2001, the local government has launched the ecological water conveyance project for the Tarim River Basin, implementing unified water scheduling and emergency ecological water transport for downstream rescue, restoration, and protection (Ablekim et al., 2016; Chen et al., 2019). From 2000 to the end of 2018, 19 ecological water transfers (27 phases) were conducted, delivering a total volume of 707.0$\times10^{8}$ m^3 (Fig. 1), with water reaching Taitema Lake more than 16 times.

The study area is geographically located at 39°00 -41°30 N and 86°00 -89°30 E (Fig. 2). Taitema Lake is the lowest point in the region at 801.50 m. To investigate all areas affected by ecological water conveyance, we established buffer zones of 30-50 km on both sides of the main conveyance channel, focusing on the region between these buffer zones.

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3. Methods

3.1 Data Acquisition

This study used Landsat TM, ETM, and OLI images from 1990, 2000, 2010, and the summer and autumn of 2018. These included multi-scene remote sensing data with track numbers 143/31, 142/31, 142/32, 142/33, 141/31, 141/32, 141/33, 141/34, and 140/33. We geometrically corrected the 2000, 2010, and 2018 images using an image-to-image registration method based on the 1990 images. After correction, the image data were mosaicked from nine sets of remote sensing images. We selected the scene with the largest area and best data quality as the reference image and adjusted other images accordingly. The FLAASH module in ENVI 5.3 software was used for atmospheric correction to eliminate atmospheric effects.

3.2 Random Forest Algorithm

The random forest (RF) algorithm is an ensemble learning method for data classification and regression (Breiman, 2001). Compared with other methods, RF performs well with smaller training sample sets, requires shorter computation time, and provides more accurate results through out-of-bag error estimation (Demarchi et al., 2014). RF has proven to be a highly robust discrimination method when remotely sensed spectra represent combinations of various materials. The algorithm was implemented using the image RF toolbox of EnMAP-Box v1.3. Figure 3 shows the methodological flowchart from imaging to results, including pre-processing.

Based on land use/land cover characteristics and planning in the lower reaches (He et al., 2010), we classified land use/land cover units according to Level-1 of the China land resource classification system, including meadowland, forestland, wetland, farmland, artificial surfaces, and other types such as Gobi, bare soil, and deserts (Fig. 4). The overall classification accuracies were 82.27%, 85.92%, 83.21%, and 87.21% for 1990, 2000, 2010, and 2018, respectively, meeting the requirements for land use/land cover monitoring.

3.3.1 Single Land Use Dynamic Index (P_1)

The single land use dynamic index (P_1; %) indicates quantitative changes in a particular land use/land cover pattern for a given region over a specific time period (Wang et al., 2017).

$$P_1 = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

where U_a and U_b represent the quantities of a particular land use/land cover pattern in the early and late stages of the research period (km^2), respectively, and T denotes the timespan (years).

3.3.2 Spatial Variability of a Single Land Use Pattern (P_2)

The spatial variability index (P_2) was introduced because P_1 only reflects quantitative changes but not the degree of spatial change. The P_2 (%) value reveals the dynamic degree of spatial change in specific land use/land cover patterns (Wang et al., 2017).

$$P_2 = \frac{\Delta U_{in} + \Delta U_{out}}{2U_a} \times \frac{1}{T} \times 100\%$$

where ΔU_{in} and ΔU_{out} represent the areas transferred into and out of a land use/land cover type (km^2), respectively, during the study period.

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4. Results

4.1 Spatial Distribution of LUCC

The distribution of land use/land cover patterns in 1990, 2000, 2010, and 2018 (Fig. 4) reveals LUCC characteristics over the 29-year study period. To explore these changes more accurately, we calculated a transition matrix for 1990 and 2018 (Table 1). LUCC varied significantly, covering 2644.34 km^2 or 15.79% of the total area (16,761.03 km^2).

Forestland covered the largest area in 2018 (5303.06 km^2), representing an increase of 284.55 km^2 (5.67%) compared to 1990. Meadowland area was largest in 1990 (722.14 km^2) and smallest in 2010 (493.09 km^2), decreasing by 103.34 km^2 (14.31%) between 1990 and 2018. Farmland area increased continuously, covering 361.20, 517.11, 690.67, and 807.88 km^2 in 1990, 2000, 2010, and 2018, respectively, for a total increase of 446.68 km^2 (123.66%). Wetland area showed the greatest increase of 533.42 km^2 (216.77%), more than doubling in size. Artificial surfaces increased from 26.39 km^2 in 1990 to 83.90 km^2 in 2018, a growth rate of 217.96% (57.51 km^2). In contrast, other land use/land cover types (Gobi, bare soil, deserts) decreased by 1218.83 km^2 or approximately 11.75% in 2018 compared to 1990.

To better analyze the area, location, and trend changes of LUCC, we conducted a superposition analysis of the 1990 and 2018 classification maps (Fig. 5). Artificial surfaces such as mining fields and transportation lands expanded rapidly by 217.96% from 1990 to 2018, primarily converted from meadowland (13.77%), forestland (8.54%), farmland (12.02%), and wetland (0.10%). Wetland area increased by 533.42 km^2 (216.77%), mainly converted from other land types (42.50%), forestland (31.27%), and meadowland (8.20%). Farmland increased by 446.68 km^2 (123.66%), primarily replacing forestland (35.15%) and meadowland (19.13%). Meadowland was mainly replaced by farmland (19.13%) and artificial surfaces (13.77%), while Gobi, bare soil, and deserts were converted primarily to artificial surfaces (43.80%) and farmland (42.50%). Although artificial surfaces did not occupy a large proportion of the study area by 2018, their growth rate was substantial, increasing from 26.39 km^2 to 83.90 km^2 (217.92%).

4.2 Land Use Dynamic Indices

Table 2 presents P_1 and P_2 values for the periods 1990–2000, 2000–2010, and 2010–2018.

The P_1 values for meadowland and forestland were negative during the first two decades (1990–2000 and 2000–2010), indicating area decreases. Meadowland declined sharply, reaching a minimum of -2.63% during 2000–2010. During 2010–2018, P_1 values for meadowland and forestland were 2.66% and 0.98%, respectively, indicating recovery. The total increase in P_1 from 2000 to 2018 was 5.29% for meadowland and 1.11% for forestland, demonstrating rapid recent growth. Farmland area increased across all three decades, as shown by positive P_1 values. Wetland area decreased from 1990 to 2000 (P_1 = -1.06%) but increased substantially during the latter two decades with P_1 values of 6.71% and 11.36%, coinciding with increased water supply facilities. Artificial surfaces showed positive P_1 values during 2000–2010 (12.54%) and 2010–2018 (0.84%), with more significant changes during 2000–2010 that decreased after 2010. Other land types such as Gobi, bare soil, and deserts exhibited successive decreases in P_1 values (-0.12% and -0.98% for 2000–2010 and 2010–2018), indicating steady decline.

The P_2 values reveal that meadowland and forestland areas generally increased from 1990 to 2018, though trends varied significantly. P_2 values for meadowland and forestland during 2010–2018 were 9.30% and 4.35%, respectively, indicating significant spatial dynamics and extensive land conversion in late 2009. Farmland P_2 values showed minimal changes across the three periods (4.31%, 3.79%, and 4.73%), implying steady conversion. Wetland P_2 values demonstrated an increasing trend (3.11%, 7.42%, and 17.31%), with the largest value in 2010–2018. Artificial surfaces had higher P_2 values during 2000–2010 and lower values during 2010–2018, suggesting reduced spatial disturbance impacts.

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5. Discussion

5.1 Trends of LUCC

Effective utilization of remote sensing data to analyze LUCC requires consideration of three aspects: location, direction, and process (Hasselmann et al., 2010; Jiang et al., 2015). Understanding change locations is vital for ecosystem monitoring and helps analyze and explain causes (Huang et al., 2006; Chen et al., 2008). Analyzing LUCC in response to ecological changes and human intervention is useful for understanding trends (Li et al., 2017; El-Tantawi et al., 2019). This study analyzed LUCC using satellite images from 1990, 2000, 2010, and 2018, with superposition of classification maps facilitating understanding of changes, locations, and trends.

The results indicate substantial farmland development near Qiala Reservoir during the study period. Most forestland extending outward from both river sides toward the desert and Gobi has become wetland, suggesting expanded water-receiving areas for vegetation (Ye et al., 2010; Keyimu et al., 2017). By 2018, most meadowland around Daxihaizi Reservoir had converted to forestland and partially to wetland. The small river course downstream of Daxihaizi Reservoir has widened significantly, forming a larger channel with numerous puddles and pits. Farmland area around Tikanlik Town (40°37 47.53 N, 87°41 23.91 E) in Ruoqiang County increased substantially, forming contiguous tracts. Notably, Taitema Lake had no water in 1990 and 2000, but water volume increased from 2010 to 2018, making it the second largest lake in southern Xinjiang. The surrounding environment improved simultaneously, with forestland area on both river sides increasing by 284.55 km^2 (5.67%), primarily in river overflow and stagnant pool areas. This suggests that river overflow promoted local vegetation recovery and the formation of fragmented, irregular forestland.

5.2 LUCC Responses to Ecological Water Conveyance

To understand LUCC responses, we analyzed wetland and vegetation areas (including forestland and meadowland) from 1990 to 2018. Wetland area changed in the order: 2000 < 1990 < 2010 < 2018 (Fig. 6), with similar areas in 1990 and 2000, increasing from 368.08 km^2 in 2010 to a maximum of 786.10 km^2 in 2018. The 11th water conveyance project in 2010 (June–November) lasted 139 days with a total volume of 3.89$\times10^{8}$ m^3 (Fig. 1). In 2018, two conveyance periods occurred in February and August, totaling 88 days and 4.29$\times10^{8}$ m^3—an increase of 0.39$\times10^{8}$ m^3 compared to 2010. This demonstrates substantial wetland improvement.

Vegetation area followed the trend 2010 < 2000 < 1990 < 2018 (Fig. 6), decreasing by 138.20 km^2 between 1990 and 2000 and by 241.81 km^2 between 2000 and 2010, but recovering with a 609.21 km^2 increase between 2010 and 2018. This indicates a degradation-then-restoration process.

Many studies suggest that water conveyance benefits require several years to become visible and cannot be observed immediately (Wan, 2012; Guo et al., 2017; Wang and Guo, 2018). Similar to gradual pre-conveyance vegetation degradation, ecological responses of downstream vegetation and groundwater are slow on spatio-temporal scales (Chen et al., 2015a, b; Keyimu et al., 2017). We analyzed relationships between vegetation area in 2010 and 2018 and previous years' water conveyance (2009 and 2017). In December 2009, cumulative conveyance lasted 26 days with 0.11$\times10^{8}$ m^3, reaching Kaerdayi. In 2017, conveyance occurred in April, May, and December, totaling 215 days and 8.33$\times10^{8}$ m^3, affecting 2018 vegetation growth. Additionally, early 2018 conveyance in February addressed spring ecological water supply. Annual vegetation area changes were positively correlated with cumulative ecological water conveyance from previous years, with one-, two-, three-, four-, and five-year cumulative volumes responding to LUCC. Therefore, short-term and long-term effects of cumulative ecological water conveyance effectively promote natural vegetation restoration along both river sides (Ye et al., 2009; Zhang et al., 2013).

Variations in vegetation and wetland areas are influenced by multiple factors including climate, water volume, conveyance days, timing, average conveyance rate, and human factors (Lu and Jiang, 2009; Bai et al., 2015; Xu et al., 2015; Ling et al., 2019; Wang et al., 2020). This study indicates that river runoff in both vertical and horizontal directions is the main groundwater recharge source in the lower reaches, with groundwater level fluctuation amplitude gradually decreasing with distance both vertically and horizontally (Wu and Cai, 2004; Yu et al., 2012; Li et al., 2017). Remote sensing interpretation and field monitoring reveal that shallow groundwater levels increased due to ecological water conveyance. Monitoring data show groundwater depth increased from 9.8–10.1 m to 2.1–5.3 m at 1 km from the main channel, while mineralization increased from 1.1–3.0 g/L to 5.3–7.8 g/L during 2000–2017 (Ablekim et al., 2016; Chen et al., 2019).

Previous studies showed vegetation in the lower reaches has been restored, with area increasing to 2285.00 km^2 (a 362.00 km^2 increase). Sandy area decreased by 854.00 km^2, and plant species increased from 17 to 46, including hogweed, white thorn, camel thorn, reed, sand jujube, and licorice as main types (Fan et al., 2013, 2014; Ye et al., 2014a, b; Chen et al., 2015a, b, 2020). Drought-tolerant trees and shrubs gradually recovered, and floral biodiversity was restored. After years of continuous conveyance, flooded poplar forestland reached 712.00 km^2, restoring extensive poplar forests that had died from water scarcity. Artificial surfaces showed an increasing trend while Gobi, bare soil, and desert areas decreased significantly, indicating increasing human activity impacts since 2000 (Hartmann et al., 2016; Bao et al., 2017; Huang et al., 2018). However, increased vegetation area and recovery were still concentrated in certain areas, requiring further efforts to ensure long-term, stable, and scientifically sound ecological water conveyance and rational water resource utilization.

This study explored ecological water conveyance effects from the LUCC perspective, though the effects are not limited to LUCC. LUCC is a complex process requiring consideration of human activities and climate change (Chen et al., 2020; Li et al., 2021). This study focused on ecological water conveyance impacts, but climate factors such as temperature and precipitation, plus natural factors like topography and soil organic matter content, may also affect LUCC and warrant future investigation.

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6. Conclusions

Based on multi-scene and multi-temporal remote sensing dynamic monitoring data, we investigated LUCC responses to ecological water conveyance in the lower Tarim River reaches during 1990–2018. The LUCC area was 2644.34 km^2, accounting for 15.79% of the total area. During the study period, wetland, farmland, forestland, and artificial surfaces increased, while grassland and other types including Gobi, bare soil, and deserts decreased. Improved vegetation was concentrated along both river sides in overflow and stagnant areas, indicating that river overflow promoted local vegetation restoration, particularly meadow-to-wetland and meadow-to-farmland conversions. Long-term, intermittent, and stable artificial ecological water delivery is a critical driver of ecological and environmental changes in the lower reaches.

Land use/land cover affects the regional natural environment, including groundwater, microclimates, natural vegetation, and wildlife, significantly impacting human lifestyles and living standards. Using multi-scene and multi-temporal remote sensing monitoring, this study provides guidance for rational water and soil resource development and utilization, and proposes Tarim River development strategies based on ecological security, serving as a scientific guideline for optimal water resource regulation and ecological water allocation.

Acknowledgements: This study was supported by the Key Project of National Natural Science Foundation of China-Xinjiang Joint Fund (U1803241), the Key Project of Xinjiang Uygur Autonomous Region Talent Special Plan-Tianshan Outstanding Youth (2019Q033), the Chinese Academy of Sciences (2017-XBQNXZ-B-019), and the Science and Technology Plan Major Projects of the Xinjiang Uygur Autonomous Region, China (2021A03001-3).

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Figures

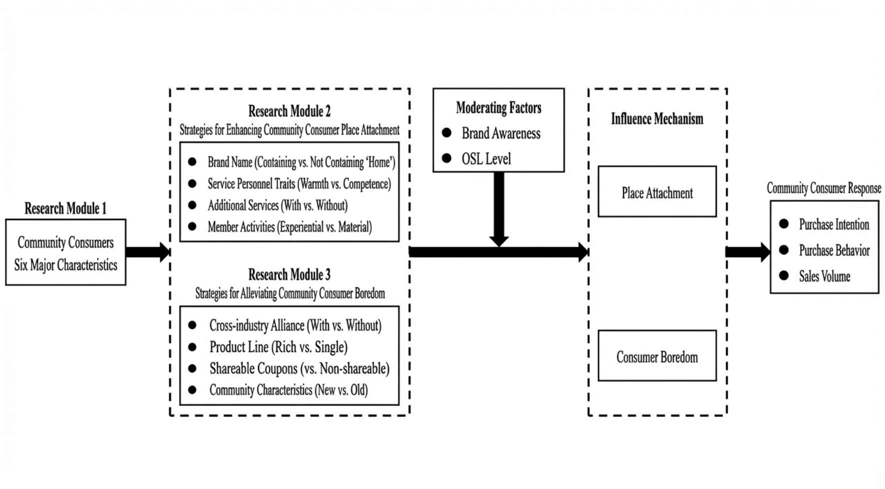

Figure 1: Figure 1

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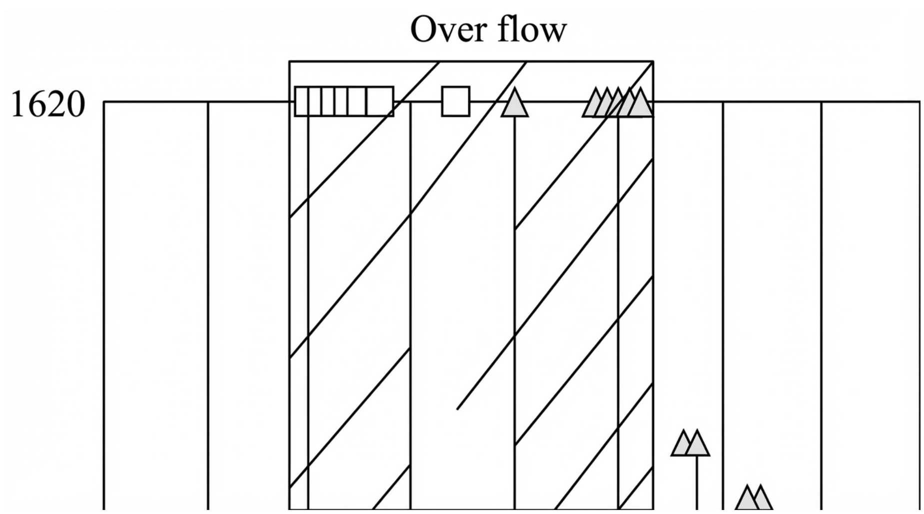

Figure 2: Figure 15