Glacial melting impact on runoff and evapotranspiration based on glacier-coupled SWAT model: A case study in the upper Shiyang River Basin, China (Postprint)

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Date: 2026-03-10T10:29:34+00:00

Abstract

Glacial meltwater constitutes a vital component of the water supply in arid and semi-arid areas. However, the influence of glacial melting on runoff and evapotranspiration under global warming remains insufficiently understood. Previous studies coupling the Soil and Water Assessment Tool (SWAT) model with glacier modules often failed to consider the spatial heterogeneity of temperature during glacial melting, potentially leading to biased estimates of meltwater volume. In this study, we developed a glacier-coupled SWAT (SWAT-glacier) model considering the digital elevation model (DEM) based temperature-driven glacial melt processes to elucidate the impact of glacial melting on hydrological processes across four river basins (Dongda, Xiying, Jinta, and Zamu) of the upper Shiyang River Basin (SYRB) in northwestern China from 1986 to 2021. Compared with the standard SWAT model, the proposed SWAT-glacier model significantly improved the simulation accuracy for both runoff and evapotranspiration. Specifically, in comparison with the standard SWAT model, the Nash-Sutcliffe efficiency of the SWAT-glacier model showed a relative improvement of approximately 0.42%-9.16% and 1.50%-10.15% for runoff and evapotranspiration, respectively, in the four river basins during the validation period. Annual glacial runoff occurred predominantly from May to October, whereas glacial melt-induced evapotranspiration peaked between June and August. From 1986 to 2021, the average contributions of glacial melt to runoff were 6.97% for Dongda, 3.06% for Xiying, 2.70% for Jinta, and 0.67% for Zamu, whereas its contributions to evapotranspiration were 9.06%, 5.14%, 3.21%, and 1.59%, respectively. This study presents a SWAT-glacier modeling framework that enhances the simulation of hydrological processes in cold regions. The proposed methodology can be extended to other glacierized basins to provide

valuable insights into water resource management under climate change.

Full Text

Preamble

J Arid Land (2026) 18(2): 216–234 doi: 10.1016/j.jaridl.2025.08.001; CSTR: 32276.14.JAL.20250192 Glacial melting impact evapotranspiration based on glacier-coupled SWAT model: A case study in the upper Shiyang River Basin, China runoff CHU Jiangdong1,2, SU Xiaoling1,2*, WANG Lei3, WU Nan4, Komelle ASKARI5, WU Haijiang1,2, ZHANG Te6, XU Liujia1,2, ZHANG Qifei7 1 Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, China; 2 College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, China; 3 Shiyang River Basin Water Resources Utilization Center, Gansu Provincial Department of Water Resources, Wuwei 733000, China;

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Abstract: Glacial meltwater constitutes a vital component of the water supply in arid and semi-arid areas.

However, the influence of glacial melting on runoff and evapotranspiration under global warming remains insufficiently understood. Previous studies coupling the Soil and Water Assessment Tool (SWAT) model with glacier modules often failed to consider the spatial heterogeneity of temperature during glacial melting, potentially leading to biased estimates of meltwater volume. In this study, we developed a glacier-coupled SWAT (SWAT-glacier) model considering the digital elevation model (DEM) based temperature-driven glacial melt processes to elucidate the impact of glacial melting on hydrological processes across four river basins (Dongda, Xiying, Jinta, and Zamu) of the upper Shiyang River Basin (SYRB) in northwestern China from 1986 to 2021. Compared with the standard SWAT model, the proposed SWAT-glacier model significantly improved the simulation accuracy for both runoff and evapotranspiration. Specifically, in comparison with the standard SWAT model, the Nash-Sutcliffe efficiency of the SWAT-glacier model showed a relative improvement of approximately 0.42%–9.16% and 1.50%–10.15% for runoff and evapotranspiration, respectively, in the four river basins during the validation period. Annual glacial runoff occurred predominantly from May to October, whereas glacial melt-induced evapotranspiration peaked between June and August. From 1986 to 2021, the average contributions of glacial melt to runoff were 6.97% for Dongda, 3.06% for Xiying, 2.70% for Jinta, and 0.67% for Zamu, whereas its contributions to evapotranspiration were 9.06%, 5.14%, 3.21%, and 1.59%, respectively. This study presents a SWAT-glacier modeling framework that enhances the simulation of hydrological processes in cold regions. The proposed methodology can be extended to other glacierized basins to provide valuable insights into water resource management under climate change.

Keywords: glacial melting; Soil and Water Assessment Tool (SWAT); SWAT-glacier model; degree-day factor; climate change; Shiyang River Basin *Corresponding author: SU Xiaoling (E-mail: xiaolingsu@nwafu.edu.cn) Received 2025-04-28; revised 2025-08-24; accepted 2025-08-28 http://jal.xjegi.com; https://www.keaipublishing.com/en/journals/journal-of-arid-land/ CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration···Citation: CHU Jiangdong, SU Xiaoling, WANG Lei, WU Nan, Komelle ASKARI, WU Haijiang, ZHANG Te, XU Liujia, ZHANG Qifei. 2026. Glacial melting impact on runoff and evapotranspiration based on glacier-coupled SWAT model: A case study Journal https://doi.org/10.1016/j.jaridl.2025.08.001; https://cstr.cn/32276.14.JAL.20250192 Shiyang River Basin, China. of Arid 18(2): upper Land,

1 Introduction

As solid reservoirs, glaciers play a crucial role in regulating hydrological processes and maintaining ecological stability (Bliss et al., 2014; Chen et al., 2020; Han et al., 2023; Afzal et al., 2025). Glacial melt rates, primarily temperature-dependent, are widely recognized as sensitive indicators of climate change (Wang et al., 2017a; Brun et al., 2019). Under global warming, the global average temperature increased by 1.55°C in 2024 above pre-industrial levels (World Meteorological Organization, 2025). This results in the accelerated melting of most glaciers worldwide, leading to increased glacial runoff (Gao et al., 2010; Frenierre and Mark, 2014; Zemp et al., 2025) and consequent alterations in regional hydrological processes (Wu et al., 2025).

However, when glacier shrinkage reaches a critical threshold, known as the "glacier melting inflection point" (Wang et al., 2024a), meltwater can no longer sustain increasing runoff, resulting in subsequent water resource reductions downstream. This phenomenon may adversely affect local agricultural production, domestic water supply, and ecosystem health (Chen et al., 2017; Wiersma et al., 2022). Mid- and low-latitude mountain glaciers are generally smaller in size and more sensitive to climate change (Li et al., 2025). Under persistent warming scenarios, many of these glaciers may disappear completely. Given the ongoing glacial retreat, glacial runoff should now be considered a non-renewable resource. Therefore, understanding glacial melting and its impact on basin hydrological processes is of paramount importance for sustainable water resource management, socio-economic development, ecological conservation, and risk assessment of climate change (Frenierre and Mark, 2014).

Currently, glacial runoff estimation methods can be broadly categorized into five primary approaches (Frenierre and Mark, 2014; Wang et al., 2024a): direct observation, glacier mass balance method, water balance method, hydro-chemical tracing, and hydrological modeling.

Hydrological models are further subdivided into temperature index and energy-mass balance models. Among these, the degree-day factor method, a representative temperature index model, has been widely adopted for glacial runoff computation owing to its minimal data requirements, computational efficiency, and robust physical basis (Hock, 2003; Xu et al., 2025). Given its strong applicability and compatibility, researchers have increasingly coupled this method with distributed hydrological models such as the Soil and Water Assessment Tool (SWAT) and Variable Infiltration Capacity (VIC) models (Wu et al., 2021; Gu et al., 2024; Jia et al., 2024; Zhang et al., 2025).

The SWAT model, one of the most extensively used watershed hydrological frameworks (Yang et al., 2022; Dai et al., 2025), achieves computational efficiency through subdivision into sub-basins and Hydrologic Response Units (HRUs), enabling effective simulation of complex hydrological processes (Sharma et al., 2022; Zou et al., 2024). Previous studies have attempted to integrate glacier modules into the SWAT model (Luo et al., 2013; Yin et al., 2017; Fang et al., 2018; Adnan et al., 2019; Su et al., 2023). For instance, Adnan et al. (2019) demonstrated that incorporating the glacier module can significantly improve the simulation accuracy of the SWAT model in Qugaqie, the glacier basin of Nam Co Lake, southern Qinghai-Xizang Plateau, China; Wei et al. (2022) simulated glacial runoff in the upper Hotan River Basin of China by embedding a glacial melt algorithm into the SWAT model, and found that the contributions of glacial runoff from its two tributaries were 48.70% and 45.50%; Yang et al. (2022) applied a glacier-coupled SWAT (SWAT-glacier) model to the upper Yarkant River Basin of China, finding that glacial runoff constituted 52.50% of the total discharge, with 78.50% occurring during summer months.

While these studies confirmed that combining the degree-day factor method with the SWAT JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 model can enhance runoff simulation accuracy in glacierized basins, critical limitations persist in current implementation. Limited by the semi-distributed modeling of the SWAT model, the current implementation typically simplifies temperature inputs by using sub-basin averaged values in the SWAT model, thereby neglecting the spatial heterogeneity of temperature across glacierized basins. This simplification presents critical limitations: glaciers predominantly occupy high mountain summits and windward slopes, where temperatures are substantially lower than sub-basin averages. Given the glaciers' extreme sensitivity to temperature changes (Banerjee, 2022), this simplification is an oversimplification that likely leads to overestimating the amount of glacial melt and an increasing uncertainty in glacial runoff simulations. Furthermore, existing studies have predominantly focused on runoff calibration while neglecting other critical hydrological processes like evapotranspiration (ET), which is the dominant output flux in land surface hydrology (Merk et al., 2024; Wang et al., 2024b). The single-element characterization may compromise the model' s overall performance and limit the understanding of cryosphere hydrology interactions.

The arid zone of Northwest China hosts numerous mountain glaciers, whose glacial melt constitutes a critical component of regional water resources (Wang et al., 2017b). In some rivers, glacial contributions can exceed 30.00% of the total discharge (Zhang et al., 2012), particularly in the Tarim and Shule river basins. Current observations reveal a pronounced retreat trend of glaciers in Northwest China, characterized by significant mass loss, areal shrinkage, and an earlier onset of the melting period (Xu et al., 2025). Existing research on glacial melt in China has predominantly focused on major glacierized regions, such as the Qinghai-Xizang Plateau (Zhao et al., 2019; Chen et al., 2024a; Gu et al., 2024; Wang et al., 2024a), Tianshan Mountains (Liang et al., 2023; Chen et al., 2024b; Jia et al., 2024; Zhang et al., 2025), northern Kunlun Mountains (Wei et al., 2022; Yang et al., 2022; Xu et al., 2023), Shule River Basin (Li et al., 2019a; Wu et al., 2021), and Heihe River Basin (Wu et al., 2015). However, the Shiyang River Basin (SYRB) in the eastern Qilian Mountains remains understudied despite containing climate-sensitive glaciers that have undergone rapid deglaciation (Zhang et al., 2015; Zhang, 2022). Therefore, a thorough investigation of the impact of glacial melting on hydrological processes in this basin is both scientifically imperative and practically significant for sustainable water resource management.

Current hydrological modeling studies have predominantly either neglected or inadequately parameterized glacial melting. To bridge this gap, the study established two primary objectives: (1) developing a SWAT-glacier model incorporating digital elevation model (DEM) based temperature-driven glacial melt processes, which ensures an accurate estimation of glacial runoff; and (2) systematically accounting for the effect of glacial melting on ET. To achieve the above objectives, we used the rapidly deglaciating SYRB as a case study. First, we conducted the bias correction of meteorological data (precipitation, temperature, and ET); then, we used the corrected climate data to implement temperature-driven glacier melt models. Finally, the glacier melt computation module was embedded into a two-element (runoff and ET) calibrated SWAT-glacier model to analyze the spatiotemporal patterns of glacial runoff and melt-induced ET variations. The proposed SWAT-glacier framework provides a transferable methodology for hydrological modeling of glacierized basins.

Figure 2

Figure 1: Figure 2

2.1 Study area

The SYRB (37°02′-39°17′N, 100°57′-104°12′E; Fig. 1a [FIGURE:1]), situated in the arid zone of Northwest China, represents one of the three major inland river basins in the Hexi Corridor, covering an approximate area of 41,700.00 km2. Orographic effects lead to abundant precipitation and well-developed glaciers in the Qilian Mountains of the upper basin, forming a crucial water conservation area with high vegetation coverage (Zhu et al., 2025), while the middle and lower CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration⋯typical reaches experience scarce precipitation and resource-based water-scarce region. The upper SYRB comprises eight tributaries, among which the glaciated ones from west to east are the Dongda, Xiying, Jinta, and Zamu Rivers. The four river basins (Dongda, Xiying, Jinta, and Zamu) of the upper SYRB were taken as the study area (Fig. 1b). Figure 1b presents an overview of the basin with glacier boundaries observed in 1980, revealing a relatively larger glacier coverage in Dongda River Basin compared to the smaller glacial systems in Jinta and Zamu river basins. intense evaporation, constituting a Fig. 1 Overview of the Shiyang River Basin (SYRB) based on digital elevation model (DEM) (a) and the study area covering the four river basins (Dongda, Xiying, Jinta, and Zamu) of the upper SYRB (b)

2.2.1 DEM and soil data

We employed 30-m resolution DEM data from the Shuttle Radar Topography Mission (SRTM) for SWAT model construction, specifically for river network delineation and sub-basin division.

In addition, these data were also used to correct the temperature data. Soil data were obtained from the Harmonized World Soil Database (HWSD) provided by the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/) with a spatial resolution of 1 km.

2.2.2 Land use data and irrigation regimes

We utilized the 30-m resolution China Land Use/Cover Change (CNLUCC) dataset in 2015 provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (https://www.resdc.cn/DOI/DOI.aspx?DOIID=54). This dataset was reclassified into eight land use types (cropland, forestland, grassland, water bodies, residential land, construction land, unused land, and wetland) compatible with the SWAT model input requirements (Fig. 2

). To accurately represent different crop-specific irrigation regimes, we further classified cropland into ten distinct crop types (spring wheat, spring maize, barley, soybean, potato, oil crop, vegetable, melon, green fodder, and herb) using a randomized sampling approach that maintained consistency between sub-basin crop area proportions and county-level statistical data from the Wuwei Statistical Yearbook 2016 and Zhangye Statistical Yearbook 2015 (Bureau of Statistics of Wuwei, 2016; Bureau of Statistics of Zhangye, 2016) (Table 1).

The determination of crop irrigation regimes was primarily referenced on the study by Hu et al. (2013) and the Wuwei Municipal Water Use Quota Standards (2019) (People' s Government of Wuwei City, 2019). While these sources mainly provided irrigation schedules for the water-scarce middle and lower reaches of the SYRB, the study area is located in the upper reaches, which have comparatively higher precipitation than the middle and lower reaches of the SYRB. Based on the field investigations, the actual irrigation requirement here is approximately 50.00% of the value prescribed by these sources.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 2 Spatial distribution of land use types in the four river basins in 2015 Table 1 Area and area percentage of crops planted in 2015 Liangzhou District Tianzhu Tibetan Autonomous County Sunan Yugur Autonomous County Area (km2) Percentage of crop area (%) Area (km2) Percentage of crop area (%) Area (km2) Percentage of crop area (%) Crop name Spring wheat Spring maize Barley Potato Oil crop Vegetable Melon Green fodder

2.2.3 Meteorological and hydrological data

The daily remote sensing precipitation data were obtained from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset provided by the University of California, Santa Barbara, USA (https://data.chc.ucsb.edu/products/CHIRPS-2.0/), with a spatial resolution of 0.05°$×0.05°.Zhangetal.(2020)demonstratedthattheCHIRPSprecipitationproductexhibitsthehighestaccura
//slt.gansu.gov.cn/slt/c115183/syindex1618275301677.shtml).Dailytemperaturedata(maximum,minimum,
surfacemeteorologicaldatasetforChinawithaspatialresolutionof0.25°×$0.25°. All meteorological data cover the period from January 1981 to December 2021.

Given the pronounced spatial heterogeneity of precipitation and temperature due to topographic influences, we employed monthly observed precipitation data to correct the daily remote sensing precipitation data, and used DEM data to correct temperature data. Daily solar radiation was calculated using latitude, sunshine duration, and Julian day. The monthly temperature lapse rates for the SYRB were adopted from the findings of Wang et al. (2009).

Monthly runoff data were obtained from the Shiyang River Basin Water Resources Utilization Center of Gansu Provincial Department of Water Resources, including the Huangcheng, Xiying, CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration⋯and Nanying reservoirs and the Zamusi Hydrological Station. The data span from January 1986 to December 2021 for the Huangcheng and Nanying reservoirs and the Zamusi Hydrological Station, and from January 2000 to December 2021 for Xiying Reservoir due to data availability constraints. ET data were obtained from five remote sensing products: Global Land Surface (PML_{ET}), Assimilation System Moderate-resolution Imaging Spectroradiometer (MODIS), and Global Land Data Assimilation System (GLDAS) Noah. Table 2 provides a detailed description of their respective temporal coverage and spatiotemporal resolutions. All ET data were uniformly resampled to a monthly temporal resolution. (GLASS), ETMonitor, Penman-Monteith-Leuning ET Table 2 Basic information on the remote sensing evapotranspiration (ET) products Product GLASS ETMonitor PML_{ET} MODIS GLDAS Noah Spatial resolution Temporal resolution Time range 0.05° 500 m 500 m 0.25° Monthly March 2000–December 2018 June 2000–December 2019 March 2000–December 2021 January 2001–December 2021 Monthly January 2000–December 2021 Note: GLASS, Global Land Surface Assimilation System; PML_{ET}, Penman-Monteith-Leuning ET; MODIS, Moderate-resolution Imaging Spectroradiometer; GLDAS, Global Land Data Assimilation System.

2.2.4 Glacial boundary data

Currently, the widely used glacier boundary datasets in China, such as the Chinese Glacier Inventory and Randolph Glacier Inventory (RGI), can only represent snapshots of glacier extents at specific time points and cannot reflect dynamic glacier changes. This study employed the glacier boundary data (Li et al., 2019b) from the National Tibetan Plateau Data Center (https://doi.org/10.11888/Geogra.tpdc.270234), which comprise of eight temporal records (1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015). Given the substantial interannual variability in glacier mass balance compared to relatively gradual changes in areal extent, we assumed constant glacial areas over short periods and extended these eight records to reconstruct annual glacier boundaries from 1981 to 2021 by applying the 1980 data for 1981-1983, 1985 for 1984-1988, 1990 for 1989-1993, 1995 for 1994-1998, 2000 for 1999-2003, 2005 for 2004-2008, 2010 for 2009-2013, and 2015 for 2014-2021.

2.2.5 Terrestrial water storage anomaly (TWSA) data

The TWSA dataset was derived from the Gravity Recovery and Climate Experiment (GRACE) mascon solutions (version RL06) provided by the Center for Space Research (CSR) at the University of Texas in Austin, USA (http://www2.csr.utexas.edu/grace/RL06_{mascons}.html), covering the period from April 2002 to December 2021, with data gaps filled using the approach developed by Chu et al. (2023a). This dataset, which encompasses various hydrological components including ice, snow, soil moisture, canopy water, surface water, terrestrial biomass water, and groundwater (Khanal et al., 2024), provides a comprehensive representation of integrated terrestrial water storage variations. Consequently, this dataset has been incorporated into water balance equation calculations in several hydrological studies (Pascolini-Campbell et al., 2020; Bai et al., 2025).

2.3.1 Bias correction of meteorological data

Owing to inherent sensor errors and uncertainties in retrieval algorithms, remote sensing products (e.g. precipitation and ET) exhibit certain biases in topographically complex mountainous regions (Khatakho et al., 2024). Furthermore, the scarcity of in-situ stations in the study area means that the CN05.1 temperature dataset, which was interpolated from observational data, fails to account for DEM-induced temperature variations. Given that the accuracy of meteorological data is JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 crucial for enhancing hydrological model performance, we implemented bias correction procedures for precipitation, temperature, and ET data.

Precipitation serves as the primary water resource input for river basins. This study employed monthly rain gauge observations to conduct bias correction on the daily CHIRPS precipitation data:

Ks,j=Pa,s,j/Pc,s,j, where Ks,j represents the correction coefficient for the rain gauge station s in month j; and Pa,s,j and Pc,s,j denote the mean observed and remote-sensing precipitation values (mm), respectively, for station s in month j. The basin-specific correction factor for month j (Kj) was derived by averaging the correction coefficients from all rain gauge stations within each upstream basin, enabling daily precipitation bias correction using the following equation: where Pd,i,j represents the bias-corrected precipitation on day i of month j (mm); and Pc,i,j denotes the original remote-sensing precipitation value on day i of month j (mm).

Pd,i,j=Pc,i,j×Kj, DEM is a critical factor influencing temperature distribution. Given the absence of in-situ temperature observations within the study area, each grid point in the CN05.1 dataset was treated as a virtual meteorological station. Considering the decreasing trend of temperature with increasing DEM, station-level temperatures were first normalized to a sea-level reference elevation using the method of Chen et al. (2011):

Th=T0+A×H, where Th represents the sea-level adjusted temperature (°C); T0 indicates the temperature of virtual stations (°C); A is the temperature lapse rate (°C/100 m); and H denotes the DEM of virtual stations (m). The adjusted temperatures were then spatially interpolated using bilinear interpolation, with a subsequent DEM-based correction:

TDEM=Ts-A×HDEM, where TDEM indicates the final 1-km resolution temperature simulation after DEM correction (°C); Ts represents the bilinearly interpolated temperature field (°C); and HDEM is the 1-km resolution DEM (m).

The adaptability of remote sensing ET data varies greatly in different regions (Ju et al., 2024), necessitating accuracy assessment and bias correction. The water balance method was employed for ET product validation:

ETa=P-R-ΔTWS, where ET is the water balance-derived ET (mm); P is the precipitation (mm); R denotes total runoff (mm); and ΔTWS represents the terrestrial water storage anomalies (mm). The optimal-performing ET product was subsequently corrected using the Delta method (Ju et al., 2024).

2.3.2 Calculation of glacier melt based on the degree-day factor method

The degree-day factor method (Chen et al., 2017) has been widely adopted for large-scale glacier mass balance and melt runoff calculations due to its reliable performance at watershed scales, minimal data requirements, and computational efficiency. The glacial melt amount was computed M=PDD×DDFice, where M represents the glacier meltwater equivalent (mm); PDD denotes positive cumulative temperature accumulated from daily mean temperatures (°C); and DDFice is the ice degree-day factor (mm/(°C•d)). DDFice is generally calculated by combining field observations and remote sensing data. Based on the geodetic method, Li (2022) obtained the results of glacier surface elevation change and calibrated the DDFice of Lenglongling in the SYRB. Following Li (2022), a value of 6.20 mm/(°C•d) was adopted for the upper SYRB in this study.

2.3.3 Concept of SWAT model construction considering the glacial melt processes

Precipitation, snowmelt, and glacial melt collectively constitute the hydrological inputs to the watershed system; however, the standard SWAT model lacks explicit representation of glacial CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration···melt processes. To address this limitation, we first developed a glacial melt model based on DEM-based 1-km resolution temperature data and the degree-day factor method, and then aggregated the computed daily glacial melt volumes to each sub-basin scale. Subsequently, to ensure consistency in the data format and spatial scale between the meteorological inputs and glacial melt estimates for SWAT modeling, each sub-basin centroid was designated as a virtual meteorological station, with meteorological variables calculated using inverse distance weighting interpolation. Finally, the combined daily precipitation and glacial melt volumes were incorporated as modified precipitation inputs into the SWAT model. The SWAT model has a complete description of the evaporation process of the HRU (Liu et al., 2022), so the sublimation/evaporation of the glacier regions was not separately calculated here.

2.3.4 Setup of the SWAT model

The SWAT model is a semi-distributed hydrological model that characterizes watershed spatial heterogeneity through sub-basin and HRU delineation, enabling the simulation of spatiotemporal variations in climatic factors, underlying surface characteristics, and agricultural management practices on hydrological processes (Jin et al., 2023; Schaffhauser et al., 2023). In this study, the SWAT model was configured as follows: (1) a minimum catchment area threshold of 10,000 hm2 was applied for sub-basin delineation and stream network generation using DEM data; (2) three slope classes (0.00%–10.50%, 10.50%–46.60%, and 46.60%–100.00%) were defined with area thresholds of 10.0% for land use, soil type, and slope combinations; and (3) recognizing agricultural irrigation impacts, the minimum crop area threshold was set to zero to ensure that all crop types were included in HRU generation. This configuration yielded 7, 11, 7, and 3 sub-basins with 141, 453, 349, and 129 HRUs for the Dongda, Xiying, Jinta, and Zamu river basins, respectively. The model was subsequently executed using meteorological data and irrigation scheme inputs.

The warm-up period for this model was set to 1981–1985. For the Dongda, Jinta, and Zamu Rivers, the runoff calibration and validation periods spanned 1986–2005 and 2006–2021, respectively. Due to data constraints in Xiying River, the periods 2000–2011 and 2012–2021 were used for calibration and validation, respectively. All four basins shared identical ET calibration (March 2000–December 2010) and validation (2011–2018) periods. Given the minimal anthropogenic impacts in the basins and relatively stable underlying surface conditions over extended periods, the Xiying River' s calibrated parameters were deemed applicable for the period This study constructed individual SWAT models for the four river basins, with each model undergoing multi-objective calibration using monthly outlet runoff and sub-basin scale actual ET data. We performed parameter sensitivity analysis, calibration, and validation using the SUFI-2 algorithm within the SWAT-CUP 2019 software (version 5.2.1.1), where parameter sensitivity was evaluated through t-statistic values (with larger absolute t values indicating higher sensitivity).

Referring to the theoretical basis of the SWAT model, we analyzed the sensitivity of 43 parameters closely related to hydrological processes, and selected the top 15 parameters for parameter calibration by t value. The Nash-Sutcliffe Efficiency (NSE) coefficient was maximized as the objective function during parameter calibration. For multi-objective calibration, the composite NSE value was calculated using the following formula: where NSE' represents the composite NSE value; wf denotes the runoff weighting factor (set to 0.5 following Zhang et al. (2020)); NSEf is the simulated NSE for runoff; ne indicates the number of ET target variables; wem signifies the weighting factor for ET in the mth sub-basin (with equal weighting across sub-basins summing to 0.5); and NSEem corresponds to the simulated NSE for ET in the mth sub-basin.

In addition, we employed several widely used hydrological performance metrics, including the JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 coefficient of determination (R2), Kling-Gupta Efficiency (KGE), and root mean square error (RMSE), to evaluate model performance. To assess the impact of glacial melting on watershed hydrology, we first conducted parameter calibration for the SWAT-glacier model, with the calibrated parameters subsequently applied to the standard SWAT model. For clarity in the subsequent discussion, the runoff

Figure 4

Figure 2: Figure 4

variation induced by glacial melt processes is termed "glacial runoff" , while the corresponding ET variation is referred to as "glacial melt-induced ET". It should be emphasized that "glacial melt-induced ET" in this context specifically denotes the melt-induced changes in ET rather than the evaporation/sublimation fluxes directly from glacier surfaces.

3.1 Changes in the area and scale of glaciers

Figure 3 [FIGURE:3] illustrates the glacial area variations in the upper SYRB from 1980 to 2015, revealing a pronounced reduction from 60.10 to 33.61 km2, with the most pronounced decline (13.37 km2) occurring during 1985-1990. The Dongda River Basin contained the largest glacier coverage (about 50.00% of the basin' s total), followed by the Xiying, Jinta, and Zamu river basins. Glaciers $ $1.00 km2 were numerically dominant but exhibited low stability and high climate sensitivity (Zhang et al., 2015). Notably, climate-driven ablation caused divergent trends: glaciers $ $0.10 km2 increased by 28 in number and 1.06 km2 in area, whereas glaciers >0.50 km2 decreased by 23 in number and 25.14 km2 in area.

Fig. 3 Variation in glacial area in different basins (a) and variations in glacial area and number at different scales (b) in the upper SYRB from 1980 to 2015

3.2 Screening and correction of ET data

Figure 4

presents the time series of remote sensing ET products versus water balance-derived ETa for the period 2001-2021. ETMODIS and ETETMonitor systematically overestimated ETa by >150.00 mm/a, exceeding the basin' s mean annual precipitation (approximately 500.00 mm) and violating runoff generation principles. ETGLDAS Noah showed a systematic low bias (approximately 100.00 Fig. 4 Time series of various evapotranspiration (ET) data during 2001-2021 over the upper SYRB. ETa, ETPML_{ET}, ETGLDAS Noah, ETETMonitor, ETMODIS, and ETGLASS represent the ET derived from the water balance method, Penman-Monteith-Leuning ET (PML_{ET}), Global Land Data Assimilation System (GLDAS) Noah, ETMonitor, Moderate-resolution Imaging Spectroradiometer (MODIS), and Global Land Surface Assimilation System (GLASS), respectively.

CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration···mm/a) before 2013, but converged with ETa after 2013. ETPML_{ET} agreed well with ETa until 2011, but diverged significantly after 2015. ETGLASS demonstrated the closest agreement (mean absolute difference <50.00

mm/a). From 2003 to 2018, the average annual ETa, ETPML_{ET}, ETGLDAS Noah, ETETMonitor, ETMODIS, and ETGLASS were 347.36, 395.84, 259.55, 453.48, 495.14, and 342.33 mm, respectively. The difference between the ETGLASS and the water balance equation was the smallest, confirming ETGLASS' s superior accuracy for the upper SYRB. Consequently, ETGLASS was selected for model calibration, with further refinement via the Delta method yielding a correction factor of 1.015.

3.3.1 Sensitivity analysis of model parameters

The parameter sensitivity analysis conducted using the SUFI-2 algorithm identified the top 10 sensitive parameters for each basin (Table 3). The parameters related to runoff and ET processes, including channel transmission loss rate (TRNSRCH), SCS curve number (CN2), main channel width (CH_W2), soil bulk density (SOL_{BD}), saturated hydraulic conductivity (SOL_K), available water capacity (SOL_{AWC}), and soil evaporation compensation coefficient (ESCO), exhibited consistently high sensitivity across all four basins. Notably, snow-related parameters (snow melt base temperature (SMTMP) and snowfall temperature (SFTMP)) showed elevated sensitivity in the Dongda and Xiying river basins due to their higher DEMs and greater snow cover fractions.

Table 3 Parameter sensitivity ranking of the SWAT-glacier model for the four river basins Dongda River Basin Xiying River Basin Jinta River Basin Zamu River Basin Parameter t value Parameter t value Parameter t value Parameter t value TRNSRCH.bsn -20.84 TRNSRCH.bsn TRNSRCH.bsn TRNSRCH.bsn CH_K2.rte CH_K2.rte SOL_{BD}.sol SOL_{BD}.sol CN2.mgt CH_W2.rte CN2.mgt SOL_K.sol CH_W2.rte SMTMP.bsn CH_L2.rte SOL_{BD}.sol CN2.mgt SOL_K.sol CANMX.hru CN2.mgt SOL_{AWC}.sol SOL_{AWC}.sol SOL_K.sol ESCO.hru SOL_{BD}.sol CH_L2.rte CH_W2.rte LAT_{TTIME}.hru SFTMP.bsn SMTMP.bsn SLSUBBSN.hru CANMX.hru SOL_K.sol LAT_{TTIME}.hru CH_K2.rte SLSUBBSN.hru SOL_{AWC}.sol CANMX.hru CH_L2.rte CH_W2.rte Note: SWAT-glacier, a glacier-coupled Soil and Water Assessment Tool (SWAT); TRNSRCH, channel transmission loss rate; CH_K2, effective hydraulic conductivity in main channel alluvium; CN2, SCS curve number; CH_W2, main channel width; SMTMP, snow melt base temperature; CH_L2, length of main channel; SOL_{BD}, soil bulk density; SFTMP, snowfall temperature; SOL_K, saturated hydraulic conductivity; SOL_{AWC}, available water capacity; LAT_{TTIME}, lateral flow travel time; CANMX, maximum canopy storage; SLSUBBSN, average slope length; ESCO, soil evaporation compensation factor.

3.3.2 Model evaluation results

The optimal parameters calibrated for the SWAT-glacier model were applied to the validation period and the standard SWAT model for comparative perfor-

Figure 6

Figure 3: Figure 6

mance assessment (Table 4).

Evaluation metrics for ET were calculated as area-weighted averages across the sub-basins. Key findings demonstrated consistent improvements in simulation accuracy with the SWAT-glacier framework. NSE for runoff in the validation period showed relative improvements of 9.16% for Dongda River Basin, 5.02% for Xiying River Basin, 0.87% for Jinta River Basin, and 0.42% for Zamu River Basin compared to the standard SWAT model; for ET, the corresponding relative increases in NSE were 10.15%, 6.61%, 1.50%, and 2.14%, respectively. The results showed performance gains in runoff and ET simulations, with accuracy enhancements proportional to glacier coverage. Notably, the enhancement of ET was greater than that of runoff. The SWAT-glacier model achieved robust validation statistics, with the NSE, R2, and KGE for runoff JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 exceeding 0.62, 0.66, and 0.58, respectively, and RMSE within 6.50 m3/s; for ET, the NSE, R2, and KGE surpassed 0.81, 0.88, and 0.69, respectively, and the RMSE was within 10.00 mm.

Minimal divergence between calibration and validation performances was observed, with some basins (e.g., Jinta and Zamu) showing improved validation metrics, confirming the model' s strong applicability for hydrological simulations in the upper SYRB.

Table 4 Evaluation indicators for the SWAT-glacier and standard SWAT models Model Variable River basin Dongda SWAT-glacier SWAT-glacier Xiying Jinta SWAT-glacier SWAT-glacier Calibration period Validation period Runoff Runoff Runoff Runoff Runoff Runoff Runoff Runoff Note: NSE, Nash-Sutcliffe Efficiency; R2, coefficient of determination; KGE, Kling-Gupta Efficiency; RMSE, root mean square error.

RMSE units for runoff and ET are m3/s and mm, respectively.

Figure 5 [FIGURE:5] presents the monthly simulated versus observed runoff during calibration and validation periods using the SWAT-glacier model. While the model generally captured hydrological dynamics with high consistency, two systematic biases emerged. Underestimation of peak flows during flood seasons (particularly in convectively enhanced orographic precipitation events) is likely due to rain gauge underrepresentation in high-DEM areas, despite bias correction. The reduced accuracy in low-flow simulations for the Xiying and Zamu rivers potentially reflected groundwater and soil water contribution uncertainties. Figure 6

demonstrates robust ET simulation performance across most sub-basins, although the slightly degraded accuracy in certain sub-basins resulted from adopting spatially uniform parameters rather than accounting for intra-basin heterogeneity. In summary, the SWAT-glacier model could effectively represent cryosphere- influenced hydrological processes in the upper SYRB.

3.4 Intra-annual distribution of glacial runoff and glacial melt-induced ET

Figure 7 [FIGURE:7] illustrates the intra-annual distribution characteristics of glacial runoff and glacial melt-induced ET in the upper SYRB. The glacial runoff predominantly occurred during May–October (75.88%, 98.16%, 95.28%, and 79.43% of annual totals for the Dongda, Xiying, Jinta, and Zamu rivers, respectively), driven by temperature-controlled melt dynamics. Notably, persistent baseflow during dry seasons (November–April of the next year), sustained by soil and groundwater storage, plays a critical role in maintaining riverine and ecosystem stability when precipitation is scarce. Influenced by temperature and water resources, glacial melt-induced ET peaked sharply from June to August, accounting for 89.63%, 89.36%, 84.81%, and 86.71% of the annual totals in the respective basins.

CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration ···Fig. 5 Comparison between simulated and actual runoff values in the four river basins. (a), Dongda River Basin; (b), Xiying River Basin; (c), Jinta River Basin; (d), Zamu River Basin. The black dotted line shows the calibration period on the left, and the validation period on the right.

Fig. 6 Evaluation of simulation accuracy of ET from the SWAT-glacier model in the upper SYRB. (a), NSE for calibration period; (b), R2 for calibration period; (c), KGE for calibration period; (d), RMSE for calibration period; (e), NSE for validation period; (f), R2 for validation period; (g), KGE for validation period; (h), RMSE for validation period. NSE, Nash-Sutcliffe Efficiency; R2, coefficient of determination; KGE, Kling-Gupta Efficiency; RMSE, root mean square error.

3.5 Impact of glacial melting on runoff and ET

Figure 8 [FIGURE:8] presents the contributions of glacial melt to runoff and ET in the upper SYRB during the period 1986–2021. The multi-year averages revealed distinct spatial patterns: glacial runoff depth measured 18.72, 5.63, 3.87, and 1.40 mm for the Dongda, Xiying, Jinta, and Zamu river basins, respectively, while glacial melt-induced ET was substantially higher at 28.09, 16.23, 9.31, and 4.89 mm, respectively. The total glacial runoff volume in the upper SYRB amounted to 3.15$×107*m*3,*whilethetotalglacialmelt*−*inducedETvolumereached*6.37×$107 m3. These results indicated that more than 60.00% of glacial melt was lost via ET before reaching the basin outlets. All basins JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 7 Intra-annual distribution of glacial runoff and glacial melt-induced ET in the four river basins. (a), Dongda River Basin; (b), Xiying River Basin; (c), Jinta River Basin; (d), Zamu River Basin.

Fig. 8 Contributions of glacial melt to runoff and ET in the four river basins. (a), Dongda River Basin; (b), Xiying River Basin; (c), Jinta River Basin; (d), Zamu River Basin. exhibited significant declining trends ($P<0.05$, as determined by the Mann-Kendall trend test (Chu et al., 2023b)), with glacial runoff decreasing at 0.34 mm/a for Dongda, 0.10 mm/a for Xiying, 0.19 mm/a for Jinta, and 0.03 mm/a for Zamu, and glacial melt-induced ET declining at 0.29, 0.21, 0.13, and 0.12 mm/a for the four basins, respectively.

The relative contributions showed consistent depletion, with multi-year average contributions of glacial melt to runoff accounting for 6.97% for Dongda, 3.06% for Xiying, 2.70% for Jinta, and 0.67% for Zamu, declining by 0.13%/a, 0.06%/a, 0.13%/a, and 0.03%/a, respectively. The contributions of glacial melt to ET averaged 9.06% for Dongda, 5.14% for Xiying, 3.21% for Jinta, and 1.59% for Zamu, decreasing by 0.12%/a, 0.07%/a, 0.06%/a, and 0.04%/a, respectively.

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4.1 Model applicability

As evidenced by the model performance metrics in Table 4, the SWAT-glacier model demonstrated consistent but varying improvements over the standard SWAT model in simulating both runoff and ET. The enhancement magnitude exhibited a strong correlation with glacier coverage, yielding notable accuracy gains in highly glacierized basins like the Dongda, whereas basins with limited glacial extents (Jinta and Zamu) showed marginal improvements. This glacier coverage-dependent performance pattern underscored the specialized applicability of the model for cryosphere-dominated systems. The following discussion evaluated the applicability of the SWAT-glacier in two critical aspects: (1) the methodological advancement of DEM-based temperature data implementation; and (2) its comparative advantages over existing glacial runoff studies in the SYRB.

4.1.1 Differences between the results by using sub-basin averaged and DEM-based temperature

Table 5 presents a comparative analysis of SWAT-glacier model outputs using DEM-based temperature data versus conventional sub-basin averaged temperature inputs. The results revealed systematic biases induced by the sub-basin temperature simplification. Glacier zone temperature overestimation led to exaggerated melt rates, causing substantial errors in both glacial runoff (overestimated by 14.69% for Dongda, 8.27% for Xiying, 8.72% for Jinta, and 1.11% for Zamu) and glacial melt-induced ET (overestimated by 8.45%, 6.76%, 4.50%, and 2.27%, respectively).

These results conclusively demonstrated that the precision of temperature data is paramount for the accurate simulation of glacial melt processes. Current

SWAT model implementations incorporating glacier modules typically utilize sub-basin averaged temperature data due to the model' s semi-distributed structure, systematically overestimating melt rates through DEM- induced thermal biases. Furthermore, this study employed a physically validated parameter, degree-day factor of 6.20 mm/(°C • d) from Li (2022). This approach helps reduce equifinality, a prevalent issue in melt modeling where different parameter sets (e.g., degree-day factor and temperature threshold) can produce similar results when calibrated simultaneously, as is common in many existing methods (e.g., Beven, 1993). To compensate for temperature overestimation, calibration can artificially reduce degree-day factor and increase melt temperature threshold, distorting cryosphere hydrological process representation. Therefore, compared with existing SWAT model studies embedded with glacier modules, the SWAT-glacier model construction idea proposed in this study can provide a more accurate simulation of the glacial melt processes and hydrological cycle in cold regions. The rapid deglaciation (44.08% glacial area loss during 1980–2015) positioned the upper SYRB among China's fastest-melting glacier systems. Climate projections suggested complete glacier disappearance in the Zamu and Jinta river basins by the 2070s and 2080s, respectively (Liu et al., 2021). The persistent post-1986 reduction in glacial runoff implies the passage of a "glacier inflection point" before 1986, marking a critical hydrological transition.

Table 5 Impact of differences in temperature data on the modeling results Temperature data Multi-year average during 1986–2021 River basin Dongda Xiying Jinta Digital elevation model (DEM)-based sub-basin averaged DEM-based sub-basin averaged DEM-based sub-basin averaged DEM-based sub-basin averaged Glacial runoff amount (mm) Contribution rate of glacial melt to runoff Glacial melt-induced ET (mm) Contribution rate of glacial melt to ET JOURNAL OF ARID LAND 2026 Vol. 18 No. 2

4.1.2 Comparison with existing results

Our study systematically yielded lower contributions of glacial melt to runoff compared to previous studies (Table 6), which can be attributed to two key methodological distinctions. First, existing approaches predominantly employed degree-day factor methods or simplified glacial runoff models that neglected evaporative and infiltration losses during meltwater transport, a well-documented overestimation bias explicitly acknowledged by Zhang (2022), whereas our SWAT-glacier framework fully incorporated these hydrological processes. Second, discrepancies in hydrological station selection could introduce systematic variations, as exemplified by the Xiying River, where previous studies used Jiutiaoling Station (upstream of Xiying Reservoir), whereas our reservoir-based gauge accounted for intermediate evaporative losses and tributary inputs. Differences in the selection of hydrological stations and the year of calculation further complicate the direct comparison of the results. Meanwhile, glacial runoff undergoes substantial evaporative and infiltrative depletion during routing, concurrently enhancing ET fluxes.

Consequently, the SWAT-glacier model advanced cold-region hydrology simulations by simultaneously resolving both glacial runoff generation and associated ET processes, thereby providing a more physically realistic quantification of cryospheric-hydrological interactions in the upper SYRB.

Table 6 Results of existing glacial runoff studies in the SYRB Reference Basin Outlet Study period

Method

Li et al. (2002) Chen and Qu (1992) Liu et al. (2021) Dongda Shagousi Xiying Jiutiaoling Jinta Nanying Reservoir Zamusi Dongda Shagousi Xiying Sigouju Jinta Nanying Reservoir Zamusi Dongda Shagousi Xiying Xiying Reservoir Jinta Nanying Reservoir Zamusi 1980–1989 Degree-day factor method Li (2022) Xiying Jiutiaoling Degree-day factor method Zhang (2022) Xiying Xiying Jiutiaoling Jiutiaoling Glacial runoff model (Bliss et al., 2014) Note: "/" means no study period or model used was recorded in the literature.

4.2 Uncertainties

Contribution of glacial melt to runoff (%) While the proposed SWAT-glacier model demonstrated satisfactory performance in the upper SYRB, several limitations introduced uncertainties in the simulations. Regarding the SWAT framework, precipitation data remained the primary uncertainty source in hydrological modeling (Wang et al., 2017c; Zhang et al., 2021). Although Delta correction and monthly gauge data were applied to rectify daily remote sensing precipitation, the uneven distribution of rain gauges (concentrated near outlets; Fig. 1) limits correction accuracy. For glacial melt calculations, the 8-period glacier inventory may induce errors because of temporal sparsity. The fixed degree-day factor (6.20 mm/(°C • d)) neglects elevational and latitudinal variations (Jones et al., 1999), suggesting that distributed degree-day factor could enhance precision. Furthermore, nonlinear incorporating solar radiation, DEM, and aspect warrant temperature-melt relationships CHU Jiangdong et al.: Glacial melting impact on runoff and evapotranspiration···investigation via enhanced degree-day factor methods. Methodologically, the one-way model coupling ignores glacier mass balance feedbacks (e.g., sublimation, area dynamics) (Schaffhauser et al., 2024). While some studies have coupled glacier modules with the SWAT model, its semi-distributed structure forces uniform sub-basin temperatures, which may artificially inflate melt rates and distort cryospheric hydrological parameters. Future studies should focus on refining the coupling mechanisms to address these process-scale interactions.

5 Conclusions

In this study, we developed a cryosphere-adapted SWAT-glacier model incorporating glacial melt processes and applied it to the upper SYRB, successfully simulating hydrological processes across four river basins (Dongda, Xiying, Jinta, and Zamu) while quantifying spatiotemporal variations in glacial runoff and melt-induced ET during the period 1986-2021. Glacier coverage exhibited a significant retreat from 1980 to 2015 over the upper SYRB, with river basin rankings by glacial area being Dongda>Xiying>Jinta>Zamu. The SWAT-glacier model outperformed the standard SWAT model across the river basins, demonstrating its robust applicability in cryosphere hydrological simulations. Glacial runoff predominantly occurred from May to October (75.88%-98.16% of the annual totals), whereas glacial melt-induced ET was concentrated from June to August (84.81%-89.63% of the annual totals). Based on the multi-year average from 1986 to 2021, the total glacial runoff volume in the upper SYRB amounted to 3.15$\times 107m3, whilethetotalglacialmelt - inducedETreached6.37\times$107 m3, indicating that more than 60.00% of meltwater was lost via ET before reaching the basin outlets. All river basins exhibited significant declining trends in glacial runoff throughout this period, which provides strong evidence that the upper SYRB has passed its “glacier inflection point” . The SWAT-glacier modeling framework introduced in this study enables a more accurate simulation of glacial melt dynamics and hydrological processes in cold regions. This approach offers a transferable and robust methodological foundation for enhancing hydrological modeling in glacierized basins, with promising implications for future research on climate change impacts and water resource management in high-DEM or high-latitude environments.

Conflicts of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements This research was supported by the National Key Research and Development Program of China (2022YFD1900501) and the Gansu Provincial Water Conservancy Scientific Experimental Research and Technology Extension Project (25GSLK044, 26GSLK093). We gratefully acknowledge to the Gansu Water Resources and Hydropower Survey and Design Institute, the Shiyang River Basin Water Resources Utilization Center of Gansu Provincial Department of Water Resources, the Wuwei Water Affairs Bureau, and the Liangzhou District Water Affairs Bureau for their indispensable support in data provision and policy interpretation.

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SU Xiaoling; Resources: CHU Jiangdong, XU Liujia, ZHANG Qifei; Software: CHU Jiangdong, XU Liujia; Supervision: SU Xiaoling; Validation: CHU Jiangdong, WU Nan, WU Haijiang, SU Xiaoling; Visualization:

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dong, SU Xiaoling, WU Nan, Komelle ASKARI, WU Haijiang, ZHANG Te. All authors approved the manuscript.

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Figures

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Figure 14

Figure 4: Figure 14

Figure 27

Figure 5: Figure 27