TET: An automated tool for evaluating suitable check-dam sites based on sediment trapping efficiency

Omid Rahmati[a,b], Hoda Ghasemieh[c], Mahmood Samadi[d], Zahra Kalantari[e], John P. Tiefenbacher[f], Omid Asadi Nalivan[g], Artemi Cerdà[h], Seid Saeid Ghiasi[d], Hamid Darabi[i], Ali Torabi Haghighi[i], Dieu Tien Bui[j*]

[a] Geographic Information Science Research Group, Ton Duc Thang University, Ho Chi Minh City, Viet Nam; omid.rahmati@tdtu.edu.vn

[b] Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Viet Nam

[c] Faculty of Natural Resources and Earth Sciences, University of Kashan, Kashan, Isfahan, Iran

[d] Faculty of Natural Resources, University of Tehran, Karaj, Iran

[e] Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, SE-106 91 Stockholm, Sweden

[f] Department of Geography, Texas State University, San Marcos, TX 78666, USA

[g] Department of watershed management, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

[h] Soil Erosion and Degradation Research Group, Department of Geography, Valencia University, Blasco Ibàñez, 28, 46010, Valencia, Spain

[i] Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland

[j] Institute of Research and Development, Duy Tan University, Da Nang 550000, Viet Nam

* Corresponding author's email address: buitiendieu@duytan.edu.vn

Highlights

- A trap efficiency tool (TET) was designed using the Python programming language.
- TET identified suitable check dam sites in the Hableh-Rud and Poldokhtar watersheds.
- Suitable sites for constructing check dams at four TE levels were identified.
- More than 71% and 55% of existing check dams in the 2 watersheds were improperly situated.
- TET avoids the financial waste caused by inefficient performance of constructed check dams.

Abstract

Sediment control is important for supplying clean water. Although check dams control sediment yield, site selection for check dams based on the sediment trapping efficiency (TE) is often complex and time-consuming. Currently, a multi-step trial-and-error process is used to find the optimal sediment TE for check dam construction, which limits this approach in practice. To cope with this challenge, we developed a user-friendly, cost- and time-efficient geographic information system (GIS)-based tool, the trap efficiency tool (TET), in the Python programming language. We applied the tool to two watersheds, the Hableh-Rud and the Poldokhtar, in Iran. To identify suitable sites for check dams, four scenarios (S1: TE≥60%, S2: TE≥70%, S3: TE≥80%, S4: TE≥90%) were tested. TET identified 189, 117, 96, and 77 suitable sites for building check dams in S1, S2, S3, and S4, respectively, in the Hableh-Rud watershed, and 346, 204, 156, and 60 sites in S1, S2, S3, and S4, respectively, in the Poldokhtar watershed. Evaluation of 136 existing check dams in the Hableh-Rud watershed indicated that only 10% and 5% were well-located and these were in the TE classes of 80-90% and ≥90%, respectively. In the Poldokhtar watershed, only 11% and 8% of the 207 existing check dams fell into TE classes 80-90% and ≥90%, respectively. Thus, the conventional approach for locating suitable sites at which check dams should be constructed is not effective at reaching suitable sediment control efficiency. Importantly, TET provides valuable insights for site selection of check dams and can help decision makers avoid monetary losses incurred by inefficient check-dam performance.

Keywords: Sediment, trap efficiency, water quality, watershed management, Python language, GIS

Tool information

Name of tool: TET (trap efficiency tool)

Hardware required: General-purpose computer (3 Gb RAM)

Software required: ArcGIS 10.2 (or higher versions)

Program language: Python

Tool size: 29 kb

Availability: https://github.com/mahmoodsamadi/TET

1. Introduction

Clean water is critical for human survival and public health. With the growing problem of water scarcity in arid and semi-arid environments and with ongoing population growth, the quality of limited water resources must be managed carefully to efficiently develop sustainable and consumable water (Chew et al., 2016; Kılkış, 2016). Rivers and lakes are important freshwater sources that also provide ecosystem services and lay the groundwork for socio-economic development (Song et al., 2020). Rivers constitute the most accessible source of water for human consumption, but river sediment is a troublesome challenge to sustainable management of watersheds. Sediment adversely affects water quality (the functions of rivers, lakes, and reservoirs), creating the potential for public health issues and posing challenges to the supply of clean water (Wang et al., 2019). Suspended sediment can carry viruses and bacterial pathogens and can also promote their development (Fischer and Pusch, 2001; Xie et al., 2016). High concentrations of sediment host microbiological contaminants that cause diarrheal diseases (Robert et al., 2016). Heavy suspended sediment reduces light penetration into water bodies, increases biochemical oxygen demand, enhances loading of nitrogen and phosphorus nutrients in eutrophic lakes, and contributes to diffuse pollution by spreading nutrients, pathogens, and other contaminants to nearby environments and to the consumers of untreated water (Yu et al., 2016).

Therefore, sediment control is critical in supplying clean water (Zhou et al., 2020). From a sediment management viewpoint, there is no doubt that constructing check dams can help control sediment losses from watersheds and river basins (Xiang-zhou et al., 2004; Castillo et al., 2007; Boix-Fayos et al., 2008; Pour et al., 2009; Seraji et al., 2009; Chen et al., 2010).

Comparing the commissioning or retrofitting costs of dam construction to the economic and environmental impacts of sedimentation (e.g., decline in water quality, loss of aquatic organisms and habitats, extra costs to the health sector), it is evident that check dams can provide considerable benefits if constructed adequately and at suitable locations (Beatty et al., 2013; George et al., 2016). Construction of check dams can greatly assist upstream areas, in that water retention enables the restoration of vegetation in dry conditions (Ferreira et al., 2018). They also help to reduce sediment load in reservoirs, thereby increasing the life-spans of storage dams (Pour et al., 2009; Seraji et. al, 2009). Check dams artificially enhance groundwater recharge, can be used to promote water harvesting, and can be used to help meet local water demands (Zhang et al., 2016). In areas prone to debris flows, check dams can also stop or decelerate the flow of water-borne soil and rock fragments, and can diminsh potentially significant impacts downstream (Remaître et al., 2008). Studies have also reported positive impacts on the morphology of stream tributaries downstream over long periods (i.e., centuries), as check dams can regulate stream morphology and stabilize river segments by moderating flow velocity and stream incision (Mertin, 2018). However, the costs of dam construction at the watershed scale can be exorbitant, necessitating accurate and efficient dam-site selection approaches (Grimaldi et al., 2015; Galicia et al., 2019).

Geographic information system (GIS) and remote sensing (RS) techniques have paved the way for studies examining dam-site selection in various regions of the world (e.g., McComb et al., 1990; Pandey et al., 2011; Jamali et al., 2013; Yasser et al., 2013; Ali et al., 2014; Mahmoud, 2014;

Jamali et al., 2018; Ahmad and Verma, 2018; Njiru, 2018; Koohbanani et al., 2018). Depending on the rationale and the objective of each study, various topological, geo-environmental, and climate features of landscapes have been selected for analysis (Barkhordari, 2013; Mahmoud et al., 2014). Similarly, diverse statistical, conceptual, and heuristic models employing GIS and RS techniques have been developed to identify the most suitable sites for dam construction. Fuzzy logic (Koohbanani et al., 2018), analytical hierarchy process (Yasser et al., 2013), multi-criteria decision-making (MCDM) (Njiru, 2018), decision support system (DSS) (Mahmoud, 2014; Mahmoud et al., 2014), and discriminant models (McComb et al., 1990) are some of the data-combination techniques reported in the literature. Satellites and sensors from which RS data have been extracted and repeatedly used for dam-site selection include Indian Remote Sensing (IRS-1C) and Linear Imaging Self Scanner (LISS-III) satellites (Pandey et al., 2011), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Njiru, 2018). Recently, sUAS and SfM-MVS photogrammetry were applied by Alfonso-Torreño et al. (2019). 3D models have also been used (e.g., Luffman et al., 2018).

The sediment trapping efficiency (TE) index has been widely used to assess reservoir sedimentation efficiency (Verstraeten and Poesen, 2000, 2001; Eizel-Din et al., 2010; Romero-Díaz et al., 2012; Reinwarth et al., 2018; Parsaie et al., 2018). This index estimates the efficiency of check dams based on upstream watershed area and reservoir capacity (Hadley and Walling, 1984; Siyam, 2000). It can also be used to estimate mid- and long-term TE, especially when flow and sediment data are not available (Verstraeten and Poesen, 2000; Boix-Fayos et al., 2008). Calculation of TE can reveal the total sediment yield based on the amount of sediment collected behind the check dam and considering the upstream area of the check dam in comparison with the total area of the basin (Fang et al., 2019). That it ignores stream power and geomorphometric factors is a limitation of the TE methodology, but it helps to simplify the approach and renders it applicable in data-scarce regions. To the best of our knowledge, there is no automated tool for TE calculation for a region that enables the creation of a distributed map at the watershed scale (i.e., a TE value for each pixel). Previous studies seem to employ cumbersome and time-consuming procedures. In previous studies, TE index has been calculated manually (or with the automation of Microsoft Excel) to evaluate the sediment trapping efficiency of constructed check dams and to indicate their performance in soil and water conservation projects. So far, however, no study has attempted spatial prediction of TE before constructing check dams in watersheds. Additionally, computation of TE value for all pixels in a drainage network is difficult and unfeasible in practice, especially in large basins. Moreover, modification of the final TE map requires an automated tool to execute the process in an iterative manner and to determine the optimal pattern. The novel contribution of the present study lies in the development of an automated trap efficiency tool (TET) for spatial prediction of the TE value for all pixels in a drainage network. The key objective when applying TET is to find sites with the highest sediment trapping efficiency, to enable engineers to prioritize their options and remain within the confines of their organizational budgets. The tool was designed and developed in the Python programming language and follows a straight-forward procedure for extracting suitable sites for check dam construction. TET is primarily intended to be used for soil and water conservation in Iran, but it can be applied in any watershed around the world. The Hableh-Rud and Poldokhtar watersheds in Iran were selected to test the validity of the TET approach. The main objectives of the study were to: 1) design a universally useful tool to employ in site selection for check dam construction, based on four scenarios: S1 (TE≥60%), S2 (TE≥70%), S3 (TE≥80%), and S4 (TE≥90%); 2) explore the influence of trap efficiency thresholds on spatial variations in suggested sites; and 3) evaluate the efficiency of constructed check dams in terms of trap efficiency.

2. Material and methods

2.1. Methodology: the trap efficiency concept and tool development

The TE concept was first discussed by Brown (1943), was extended by Brune (1953) to assess sedimentation in reservoirs, and has been widely used all over the world. The concept is based upon the ratio of retained sediment behind the dam to the total sediment inflow during the lifetime of a reservoir (Eizel-Din et al., 2010). The TE index is a function of the characteristics of the inflow discharge and the retention capacity of the check dam, for which upstream area (termed contribution area) and channel geometry are the main factors influencing inflow volume and reservoir capacity, respectively (Verstraeten and Poesen, 2001). Age of the reservoir, shape of the basin, characteristics of the check dam, and method of operation also influence sediment trap efficiency. However, obtaining detailed data and information for estimating the TE index of check dams over watersheds remains challenging, even in developed countries, as inflow measuring gauges have not been installed upstream of every check dam. Therefore, previous studies made a trade-off between the data requirements of an index for estimating TE and the prediction accuracy of the index (Verstraeten and Poesen, 2000). Research has shown that there is a significant correlation between TE and capacity-watershed area ratio (Brune, 1953; Siyam, 2000; Eizel-Din et al., 2010). Brune (1953) prepared a standard curve by plotting capacity-inflow (C/I) ratio against sediment trapping efficiency for sites in the USA, and successfully applied it to estimate the percentage of sediment yield based on the sediment trapped. Therefore, the C/I ratio was later selected as the main constituent of the TE index (Romero-Díaz et al., 2012; Parsaie et al., 2018; Reinwarth et al., 2018). In fact, this concept refers to the generalizability of the percentage of inflowing sediment mass that remains permanently in the reservoir. This feature keeps the TE index versatile, quantifiable, and relatively accurate based on rather simple measures (Mulu and Dwarakish, 2015).

In this study, the TE index was calculated using the following equation proposed by Brown (1943) as it is particularly simple (i.e., it uses only two parameters) and straightforward, yet it is still practical:

$$TE = 100\left(1 - \frac{1}{1 + 0.0021D\frac{C}{W}}\right) \tag{1}$$

where C denotes reservoir capacity in m^3, W denotes catchment area in km^2, and D is a parameter dictated by the characteristics of a reservoir. Theoretically, D increases with increasing retention time, average grain size, and operating methods (such as sluicing and other methods that cause a prolonged sediment-accumulation period). An average value of 0.1 is specified for D by Brown (1943). The TE index can be used for two purposes: 1) evaluating the performance of constructed check dams; and 2) estimating the amount of sediment yield, especially where flow gauges (hydrometry stations data) are not available. In previous studies, only the first one has been done (Jothiprakash and Vaibhav, 2008; Zhao et al., 2017), because calculating the trap efficiency (before constructing check dams) for all pixels within a drainage network is time-consuming and cumbersome, especially in large regions. Until this study, nobody had proposed an automated and a comprehensive geospatial analysis system for the identification of sites that are suitable for check dams.

TET was developed in Python, making it easy to embed in the ArcGIS geoprocessing toolbox. The calculation architecture of TET is simple, since only a digital elevation model (DEM) is needed to use the tool (Table 1). TET applies three main steps for identifying suitable sites for check dam construction (Fig. 1): 1) hydro-morphometric analysis, 2) sediment trap efficiency analysis, and 3) site selection of check dams. In the first step, flow direction and flow accumulation are DEM derivatives, and are used as proxies to extract the stream network. Flow direction and flow accumulation layers are generated using the *Hydrology* toolbox in ArcGIS software. The *Flow direction* tool in this toolbox creates a raster of surface flow direction from each cell to its steepest downslope neighbor. The *Flow accumulation* tool creates a raster of accumulated surface flow into each cell. Based on flow accumulation, flow path in the watershed can be found and the stream network can be generated using the *Con* function in the *Raster calculator* tool and the *Stream* tool in the *Hydrology* toolbox. Determination of the drainage network inevitably requires a fair guess of the accumulation threshold value, to generate a stream network that is as similar as possible to that formed in nature, especially in terms of channel initiation points.

In the second step (sediment trap efficiency analysis), the tool calculates the parameters *C* (reservoir capacity) and *W* (catchment area), based on volume and area functions, respectively. TET assumes that a check dam is constructed in each pixel of the stream network and calculates the corresponding potential reservoir capacity and upstream catchment area. To estimate potential reservoir capacity, TET uses the *Storage capacity* tool in the Spatial Analyst Supplemental Toolbox (https://www.esri.com/arcgis-blog/products/analytics/analytics/introducing-the-storage-capacity-tool/).

Through these processes, in the third and final step, TE is calculated for each pixel based on equation (1) and, accordingly, the preselected sites for dam construction can be compared. The TET interface is designed to be self-explanatory (Fig. S1).

Fig. 1 here

Table 1 here

In this study, four different acceptable TE classes were selected as scenarios: S1 (TE≥60%), S2 (TE≥70%), S3 (TE≥80%), and S4 (TE≥90%), and applied in both test watersheds. In addition, after preparing TE maps, existing check dam locations were added to these maps, to determine the frequency of these check dams in terms of different TE classes (i.e., <50%, 50-60%, 60-70%, 70-80%, 80-90%, and ≥90%). The efficiency and precision of constructed check dams were then inferred by comparison with other suggested sites with different TE values.

2.2. Case study

2.2.1. Study areas

This study was conducted in two regions of Iran: the Hableh-Rud (3269 km^2) and the Poldokhtar (9443.95 km^2) watersheds. The Hableh-Rud watershed (35°20′–36°00′N; 52°20′–53°00′E) is located in Tehran and Semnan provinces in northern Iran, while the Poldokhtar watershed lies in Lorestan Province in western Iran (33°04'–34°03'N; 47°12'-48°58'E) (Fig. 2). Both watersheds have a semi-humid cold climate and both are mountainous. The elevation of the Hableh-Rud watershed ranges from 968 to 4036 m a.s.l., while the Poldokhtar watershed has an elevation range of 580–3627 m a.s.l. Spatial variations in slope factor occur in the Hableh-Rud (0–72°) and Poldokhtar (0–81°) watersheds. Mean annual precipitation in the Hableh-Rud and the Poldokhtar watersheds is approximately 165 mm and 388 mm, respectively, and the main rainy season in both watersheds is from October to April. Both watersheds have extreme rainfall intensity that results in high soil erosion and sediment yield. In terms of the spatial distribution of rainfall pattern within the watersheds, data obtained from rainfall stations show that upper parts of the watersheds receive more rainfall than lower parts. Mean annual temperature ranges from 15 to 33 °C in the Hableh-Rud watershed, but is higher in the Poldokhtar watershed (16–35°C). Minimum and maximum mean temperature in both watersheds is recorded in December and July, respectively. Thirty-five rock units, diverse in lithology, are evident in both regions. Rangeland, farmland, and forest cover most of the watersheds, with the main soil types being entisols, inceptisols, and aridisols. Southern parts of the Hableh-Rud watershed are described as a badland landscape ("badland" refers to areas of unconsolidated sediment or poorly consolidated bedrock with a very dense dendritic drainage network and little or no vegetation). These lands are useless for agriculture because of their intense dissection with deep gullies and rills. Several soil erosion types, including rill and gully erosion, occur in both watersheds. The Poldokhtar watershed has experienced several landslide events, and sediment from landslides that reach rivers may affect river channel aggradation and cause flooding that reduces the storage capacity of downstream reservoirs. The Hableh-Rud and Poldokhtar watersheds are pilot watersheds for several national and international sustainable development projects. Hence, the budget allocated to soil and water conservation research is significant. Meanwhile, check dam construction continues throughout these watersheds. Hence, assessing the sediment TE of potential sites and comparing them with sites at which check dam have been constructed enables the identification of better alternatives. Since most rangeland in the study watersheds has been degraded by livestock grazing, soil erodibility has been affected. The rivers in both watersheds have historically carried considerable amounts of sediment during floods. For example, the sediment yield of the Hableh-Rud watershed ranged from 0.1 to 200 kg/m^3 in suspension and as bed load (Parhami, 1977). According to Alvandi et al. (2019), the estimated soil erosion rate was 33.4 ton/ha/year.

Both watersheds still have high sediment yield, caused by combining the semi-arid environment with anthropogenic forcing (e.g., livestock grazing, mining, and road construction). Hence, sites for check dams must be selected precisely and every check dam should have the maximum TE. In addition, financial resources are very limited which limits the number of check dams that can be constructed and requires careful allocation of resources for check dams construction. The high erosion potential in the area and budget allocation conflicts involving the public and private sectors have created an urgent need to devise a method for efficiently selecting the most effective sites for future check dams.

Fig. 2 here

2.2.2. Applying TET and comparing the results to existing dam sites

Our novel TET approach was used to determine suitable sites for check dam construction at several TE levels (≥60% (S1), ≥70% (S2), ≥80% (S3), and ≥90% (S4)) in the Hableh-Rud and Poldokhtar watersheds. Five-meter resolution DEMs provided the input data for each watershed. Sites in the stream networks of each watershed with TEs of ≥60%, ≥70%, ≥80%, and ≥90% were evaluated separately. Maps at each TE level were generated for both watersheds.

From a practical viewpoint, the TET can be used in two different ways. It can be used to assess the suitability of sites of existing check dams, or can be used to spatially assess potential sites for new construction. A comparison of the efficiencies of existing check dams entails overlaying maps of check dams with maps of sites suggested by the TET (at each TE level). Doing this showed whether the sites of existing check dams in the Hableh-Rud and Poldokhtar watersheds can achieve their purposes. The existing check dams in the study areas (n=136 in Hableh-Rud, n=207 in Poldokhtar) were assessed; a TE value was calculated for each pixel.

3. Results

3.1. Identifying suitable sites based on scenarios

Assessments of the Hableh-Rud watershed (Fig. 3) reveal the current conditions of check-dam organization. Scenario S1 (i.e., acceptable trap efficiency set as 60%) analysis indicates that there are 189 suitable sites (Fig. 3a). Reservoir storage capacities of these check dams are generally not large enough, however. Furthermore, most check dams are located at or near the suggested sites that have TE≥60%. For scenario S2 (TE≥70%) conditions, the TET indicated there are 117 sites in the watershed (Fig. 3b). Collectively, these sites had a greater reservoir storage capacity than those identified in S1. In the conditions of scenario S3 (TE≥80%), there are 96 sites appropriate for check dams (Fig. 3c). In scenario S4 (TE≥90%), TET identified 77 suitable sites (Fig. 3d). The storage capacities of the 77 sites collectively exceed total storage capacities in the other scenarios; their upstream inundation zones are not very wide as well.

Fig. 3 here

The results of TET applications to the Poldokhtar watershed (Fig. 4) show similar relationships to existing dams. In the first scenario, S1 (TE≥60%), TET indicated that there are 346 sites suitable for check dams (Fig. 4a). Some of the existing check dams are coincident with these sites. In scenario S2 (TE≥70%), there are 204 sites appropriate for check dams with the target efficiciency

(Fig. 4b). There is considerable spatial agreement of these locations and current dams. Under scenario S3 (TE≥80%), 156 sites meet the TE criterion (Fig. 4c). And for the most efficient scenario, S4 (TE≥90%), only 60 sites are appropriate. The reservoir capacities and upstream indundation areas would be optimal. Constructing check dams at these locations would yield high efficiency.

Fig. 4 here

3.2. Comparing constructed check dams and suggested sites

Comparison of the existing check dams in the Hableh-Rud and Poldokhtar watersheds to the TET-suggested sites reveals that TE of current check dams ranged considerably. Of the 136 existing check dams in the Hableh-Rud watershed (Fig. 5a), 14 (approximately 10%) have <50% TE. Furthermore, 51 check dams (37.5%) have 50-60% TE, 45 (22%) have 60-70% TE, and 53 (25.5%) have 70-80% TE. The results reveal that only 7 (only 5%) of the 136 check dams in the Hableh-Rud watershed are located at or near optimal dam sites (TE≥90%) (Fig. 5a).

In the Poldokhtar watershed, 5 dams (8%) of 207 have TE values <50% (Fig. 5b). Sixty one (29.5%) have 50-60% TE, 45 (22%) have 60-70% TE, 53 (25.5%) have 70-80% TE, and 23 (11%) have 80-90% TE. Only 17 (8%) haveTE exceeding 90%.

Fig. 5 here

4. Discussion

4.1. Identifying suitable sites for check dams in four scenarios

Sediment in river water that is used for drinking can cause human health problems like kidney stones, gallstones, and joint stiffness, and may also cause hardening of the arteries and artery blockage in severe cases (Hussain et al., 2014). Thus, sediment control is among the most important components of water quality management (Kalantari et al., 2018; Hu et al., 2019; Itsukushima et al., 2019). Building dams to control sediment can be cost-effective. A recent study found that watershed sediment yield can be reduced by up to 70% if sediment is allowed to accumulate behind check dams (Adeogun et al., 2018). Otherwise, the load can accumulate elsewhere and can damage infrastructure (e.g., roads, buildings, water intakes, and bridges) (Kalantari et al., 2017, 2019; Karlsson et al., 2017). Check dam construction at appropriate locations can prevent these problems (Garg and Jothiprakash, 2010). However, site selection for check dams is influenced by several factors and usually involves cumbersome processes in which the criteria may differ as each circumstance is distinct and the knowledge needed for specific physical processes may be difficult to acquire. As discussed by Osti and Egashira (2008), actions needed to meet all site-selection criteria (maximum efficiency, minimum cost, etc.) may cost considerable time and money, so preliminary assessments are crucial. An automated platform to complete the initial stages of site selection and prioritization for check dam construction, particularly in large basins with wide arrays of soil types and land uses, can help decision makers optimize sediment collection from both technical and economic points of view.

Simulation systems are valuable decision-support tools for environmental management and scenario-based management assessments. Development of spatial predictions using GIS is now an important objective in watershed management studies (e.g., for soil conservation and sediment control), as they may make decision-making by environmental managers and planners easier. These systems can cost-effectively and time-efficiently provide information for an initial plan with specific priorities that engineers can select, enabling awareness, understanding, and design of efficient sediment control plans. In this study, an automated tool, TET, was developed for use in identification of check dam sites with selected sediment-trapping efficiencies. TET can simplify this process, ease evaluation of alternatives, and enable modification of site-selection criteria. Site selection should not be based solely on TET results, but should include field investigations. To reiterate, the intent behind the TET framework is to make site selection easier and faster by integrating the TE criterion into current methods rather than replacing these methods. Decision makers are obliged to invest most of their budget in established management priorities. Our TET approach enables the identification of critical stream channels and the use of a budget in an economically efficient and technically expeditious manner. Eizel-Din et al. (2010) points out that check dams are designed to have limited lifespans of functionality even with regular maintenance. Therefore, it is important to site them in the most effective locations. In this study, four acceptable TE thresholds were examined in two test watersheds in Iran. The results show that TET effectively identified a number of suitable sites in each scenario (S1-S4). Geographically, sub-basins with high erosion potential upstream of dams and reservoirs, major structures such as bridges, and main urban areas would be regarded as areas most in need of check dams. The necessary number of dams and their collective sediment-trapping capacities depend directly on budgets and aims of the projects, and they must be optimized according to other watershed management practices. The spatial distribution of check dams and their site designs are dependent on local topography and construction materials; dams may be comprised of compacted earth, piles of rock, gabions filled with rock or masonry, or a gravity structure constructed across a stream or river.

4.2. Evaluating trap efficiencies of constructed check dams

TET was used to assess the TE and suitability of existing check dams in the Hableh-Rud and Poldokhtar watersheds. Analysis indicates that 71.5% (98) of 136 constructed check dams have

TE <70%. In the Poldokhtar watershed, 55.5% (114) of existing check dams in the Poldokhtar watershed have <70% TE. Although these dams successfully trap sediment (confirmed in field investigations), they could be more effective and more efficient. There may have been considerable economic losses due to the improper locations and poor functioning of 71.5% and 55.5% of inefficient check dams in these two watersheds. Quiñonero-Rubio et al. (2016) pointed out that finding the most suitable locations for constructing check dams is important, especially in flood-prone watersheds with high erosion rate and sediment yield. Most of the funds designated for check dam construction in the study areas were earmarked for sediment retention and control.

There are several reasons for the ineffectiveness of check dams sited in the past. Construction of check dams has a long history in Iran and, in practice, their locations were normally determined by experts' opinions, availability of building materials (e.g., proximity to sources of rock), road access, land uses, and riparian characteristics. These factors are practical construction issues, which was the primary focus of the experts and stakeholders. Therefore, sediment trapping efficiency was not considered in site selection. However, this study revealed the importance of TE consideration in check-dam site selection.

Sustainable management of soil erosion and sediment control in critical areas requires a multidisciplinary approach. This may include the targeting of upstream zones that are highly susceptible to erosion and sediment yield and the identification of suitable sites based on sediment TE. Such a multidisciplinary approach can reduce high erosion rates, particularly in areas affected by tillage (Novara et al., 2019), trampling (Salesa and Cerdà, 2019), forest fires (Thompson et al., 2019), land abandonment (Cerdà et al., 2018), and intensive herbicide use (Keesstra et al., 2019). Solutions are urgently needed to quickly achieve efficient soil erosion control (Albert-Belda et al., 2019) to reduce soil loss and safeguard ecosystem services.

Iran has been a leader in dam construction, and historically sedimentation has been an important issue in reservoir operation at places like the Sefidrud Dam (Hajiabadi and Zarghami, 2014; Gholami et al., 2018) and the Dez Dam (Schlegel and Dietler, 2010). Hydrographic surveys have shown the mean annual rate of reservoir capacity reduction due to sedimentation is about 0.54% (Pour et al., 2009). The Sefidrud Dam lost 41% of its capacity from 1963 to 1982 and sediment-flushing is being considered to restore some (Hajiabadi and Zarghami, 2014; Gholami et al., 2018). The high rate of dam construction, considerable erosion-enabling land cover in the headwaters of major reservoir watersheds, and budgetary limitations challenge decision makers' watershed management practices. TET, a powerful new tool for identifying appropriate check dam sites, could make such decision making more effective and less expensive.

5. Conclusions

Soil erosion and sediment yield are important threats to the sustainability of human societies, as they adversely affect the cleanliness of drinking water supplies. Check dams can help control the impacts of soil erosion, but siting dams in appropriate locations is the key to their effectiveness. Although focusing on TE can aid the identification of suitable dam sites, TE calculation for all points within large drainage networks remains challenging. An automated TET in the Python programming language was developed to identify suitable sites based on TE at specific locations. TET was applied to two test watersheds located in northern and western Iran. The main conclusions are:

- TET identified 189, 117, 96, and 77 suitable check-dam construction sites in the Hableh-Rud watershed under scenarios S1 (TE≥60%), S2 (TE≥70%), S3 (TE≥80%), and S4 (TE≥90%), respectively. And TET identified 346, 204, 156, 60 suitable sites in the Poldokhtar watershed under the S1-S4 scenarios, respectively.

- Field investigations and further analyses indicated that only seven (5%) of the 136 check dams in the Hableh-Rud watershed are located at optimal sites that could yield ≥90% TE. Only 10% of check dams have 80-90% TE and 12.5% have 70-80% TE. Therefore, 72.5% of existing check dams in the Hableh-Rud watershed are improperly sited (TE<70%) in the drainage network; the costs of poor performance of these could be high. Only 8%, 11%, and 25.5% of constructed check dams in the Poldokhtar watershed have ≥90%, 80-90%, and 70-80% TE, respectively. Approximately 55.5% are < 70% efficient.
- TET is efficiently identifies the best sites. When used at early planning stages, it can reduce the need for and size of field investigations, particularly in over large study areas. Our analyses provide evidence that check-dam siting in watersheds based on labor-intensive field visits is not optimal, and may not meet scientific standards. Inappropriate locations of check dams can diminish sediment capture and storage and reduces the cost-effectiveness of sediment-control measures. TET can increase project effectiveness by enabling prioritization, selecting the best alternatives when allocating resources across watersheds. Considering the limited financial resources, manpower, and time available, sediment control projects around the world could apply TET as an intelligence-based framework check-dam site selection.
- Research is needed to improve TET by incorporating other geo-environmental criteria, such as logistical needs (e.g., identification of sites with solid geological foundations, the design of reservoirs that minimize inundation of land surface) and other desires (e.g., dam-site accessibility by communities, and minimization of potential environmental and social impacts).

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Table 1 Input and output files to the trap efficiency tool (TET)

File type	Setting	Description
Input file	DEM layer	Import a digital elevation model (DEM). All flow directions, flow accumulation, and stream network are generated based on the DEM layer.
Input file	Stream threshold	Select a threshold to extract a stream network based on flow accumulation. This threshold determines where stream channels initiate.
Input file	Acceptable trap efficiency	Select an acceptable trap efficiency that allows TET to suggest some sites for constructing check dams. The trap efficiency (TE) of the suggested check dam sites is always higher than the acceptable TE. TE $\geq$ 90% is ideal.
Output file	Shapefile	This file includes the location of the suggested check dams that have the highest trap efficiency. Some auxiliary information is also provided in the attribute table of the layer, including catchment area (or specific area), reservoir storage capacity, and trap efficiency (TE) of each check dam.

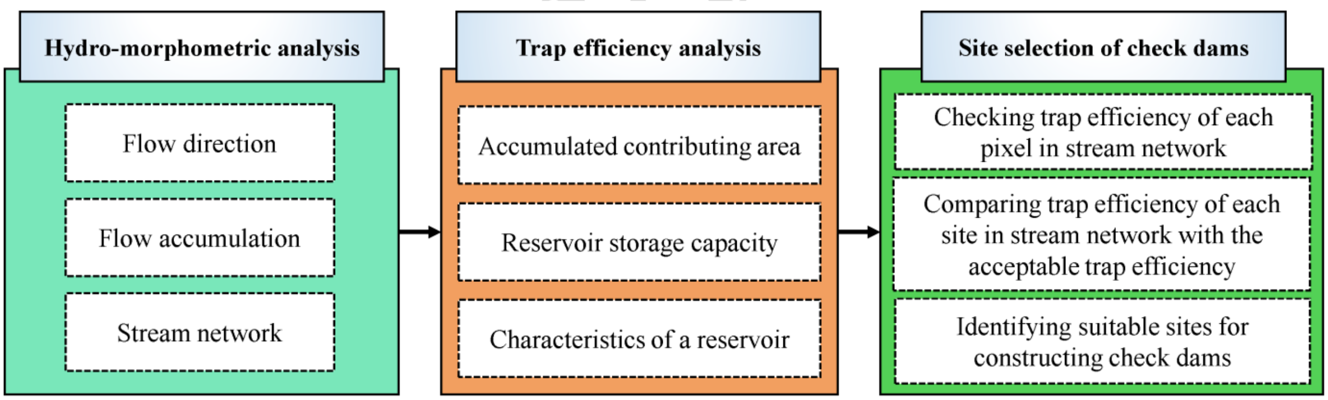

Fig. 1 A conceptual architecture for identifying suitable sites for check dam construction based on the principal of trap efficiency.

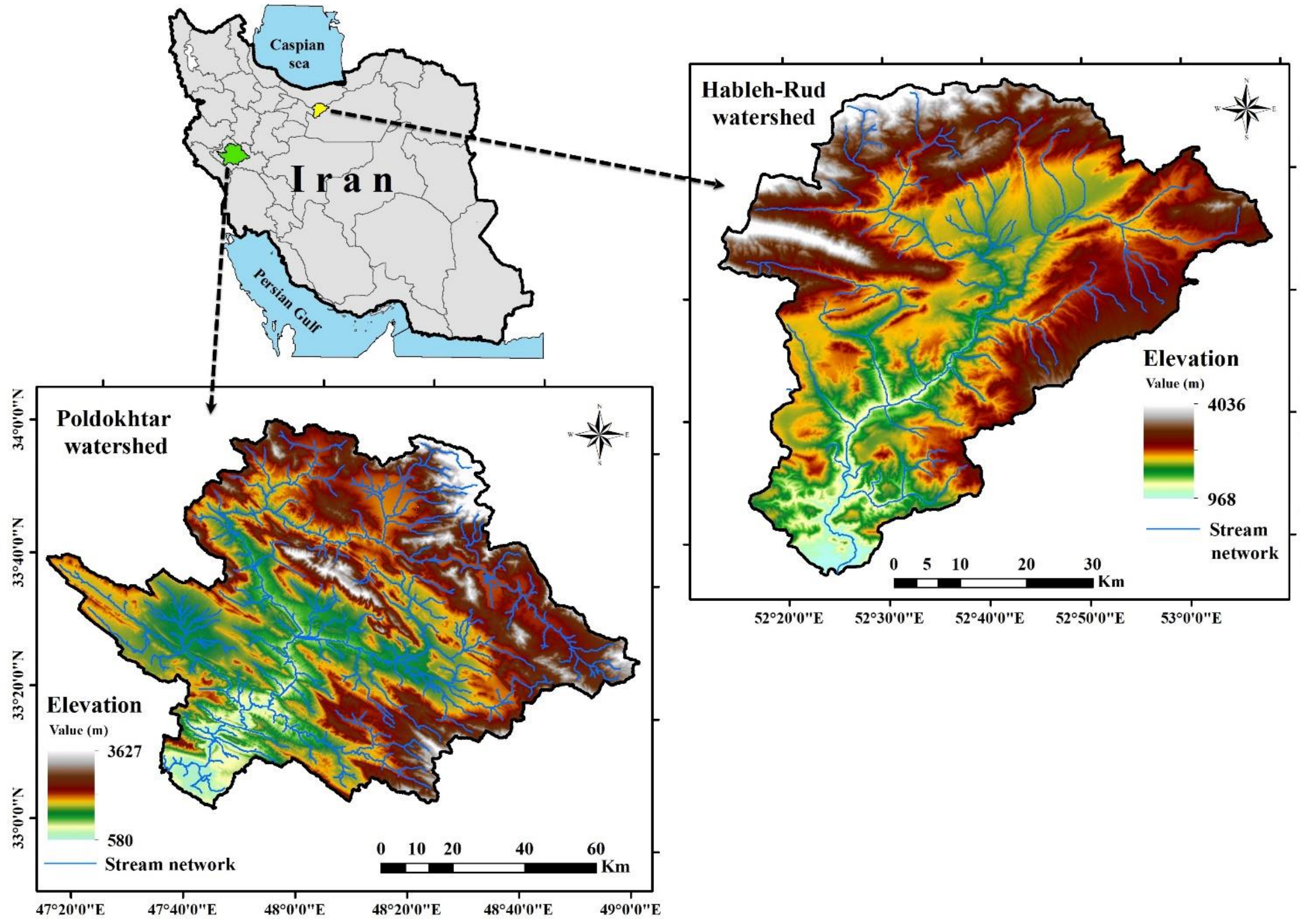

Fig. 2 The location and topography of the Hableh-Rud and Poldokhtar watersheds in Iran.

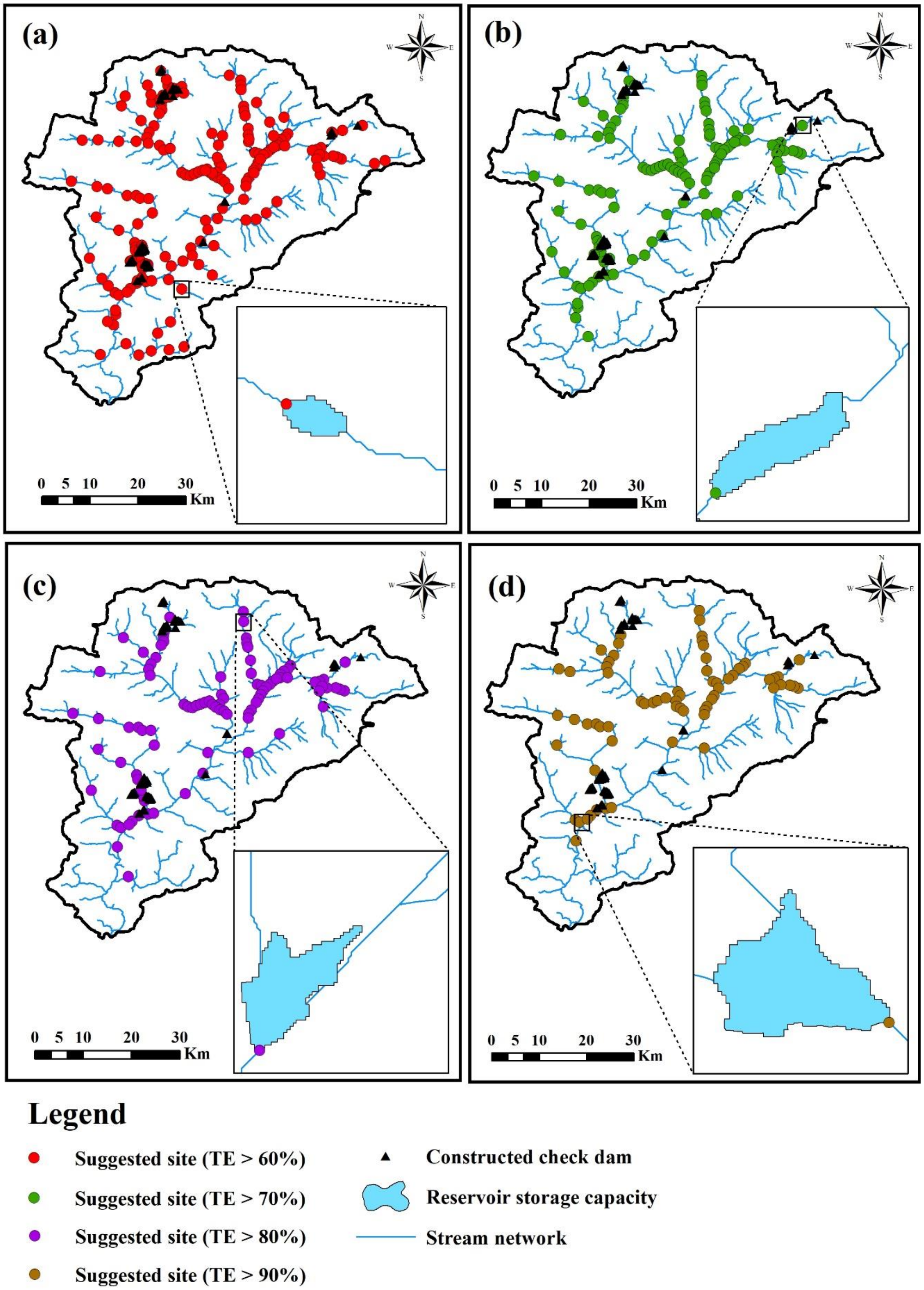

Fig. 3 Suitable sites for check dams identified by the trap efficiency tool (TET) and sites of constructed check dams in the Hableh-Rud watershed using several trap-efficiency rates: a) TE>60%, b) TE>70%, c) TE>80%, and d) TE> 90%.

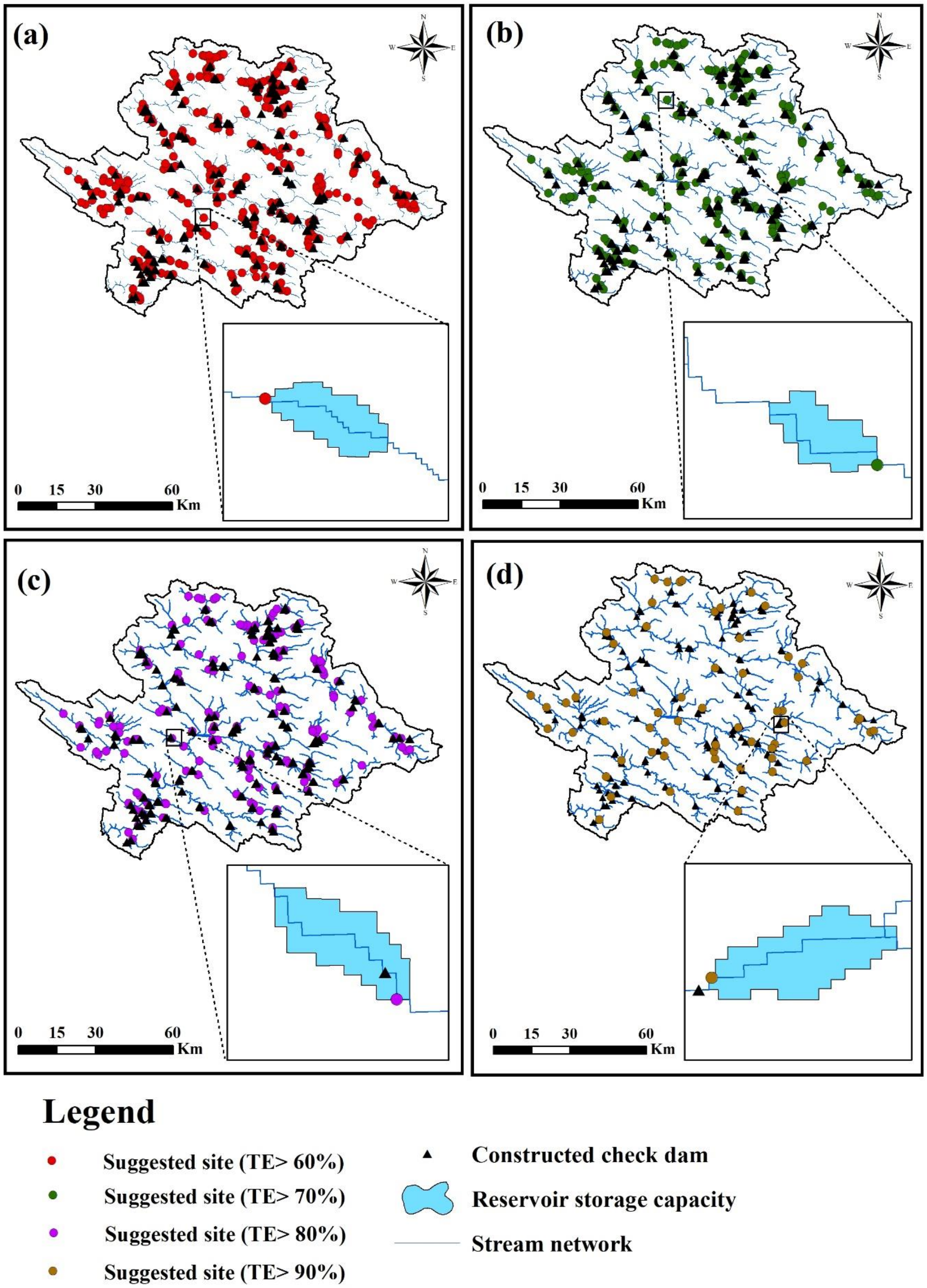

Fig. 4 Suitable sites for check dams identified by the trap efficiency tool (TET) and sites of constructed check dams in the Poldokhtar watershed using several trap-efficiency rates: a) TE>60%, b) TE>70%, c) TE>80%, and d) TE> 90%.

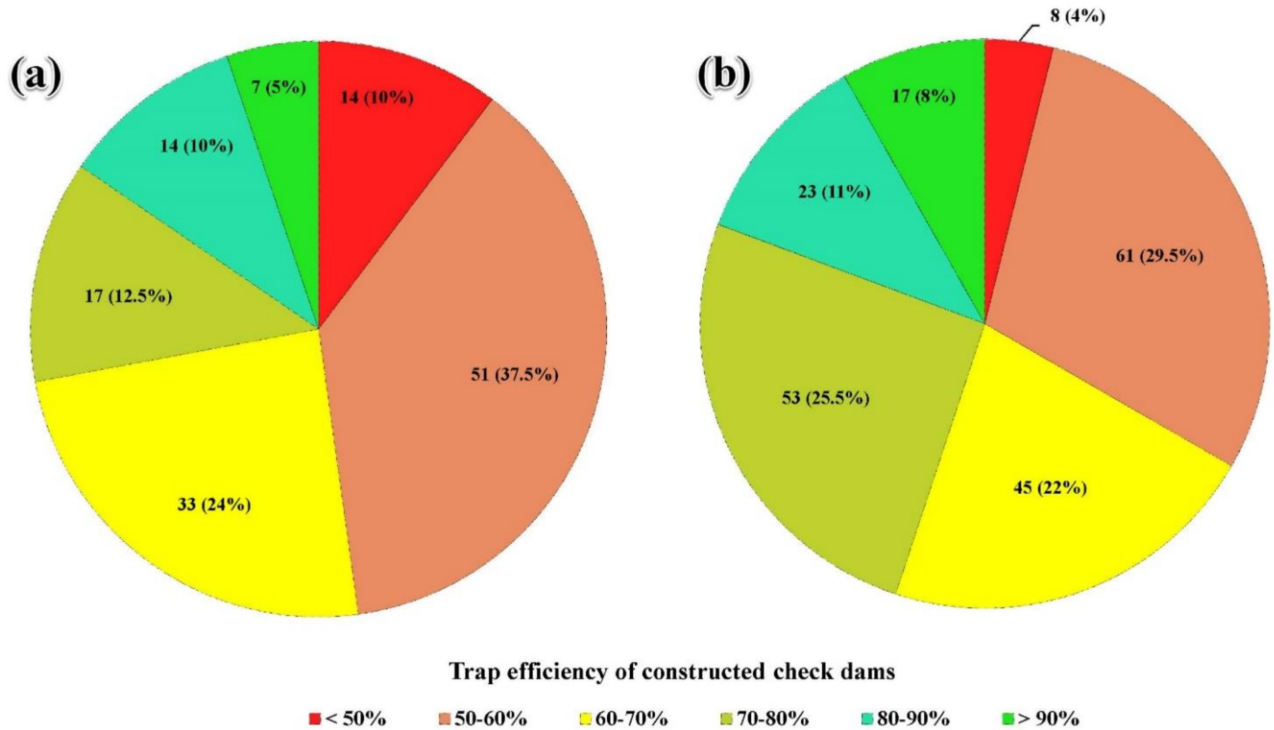

Fig. 5 Frequency of the constructed check dams by trap efficiency class in the: a) Hableh-Rud watershed, and b) Poldokhtar watershed.

"Supplementary information"

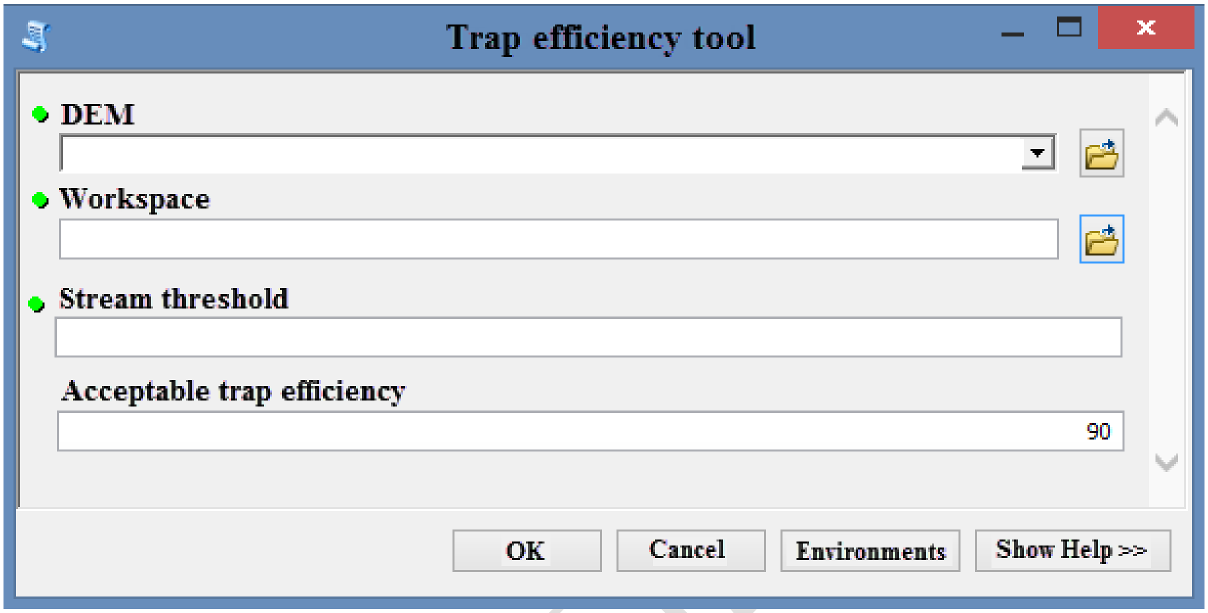

Fig. S1 View of the main window of the trap efficiency tool.