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Abstract: Surface irrigated agriculture in arid and semi-arid regions contributes to downstream environmental degradation. Changes in irrigation system operational scenarios (ISOS) can represent an economic alternative to reduce surface runoff impacts. At the same time the use of vegetative filter strips (VFS) can have a positive impact on the ecological health of rural landscapes by reducing erosion, improving water quality, increasing biodiversity, and expanding wildlife habitat. The goal of this paper is, using a combination of field data and mechanistic modeling results, to evaluate and compare the spatial effectiveness of improvements in ISOS and introduction of VFS to reduce surface runoff pollution in the semi-arid/arid furrow irrigation agroecosystem that exceeds current regulatory turbidity limits (25 NTU). Five main factor interactions were studied: four soil textures, two field slopes, three ISOS, six filter vegetation types, and ten filter lengths. Slope and runoff volume were identified as the two main drivers of sediment export from furrows. Shifting from current ISOS to less water consumptive irrigation practices reduce runoff in addition to sediment delivery to comply with environmental regulations. The implementation of 3 to 9 m vegetative buffers on experimental parcels were found to mitigate sediment delivery (greater than 90% sediment reduction) on tail drainage ditches but had limited effect in the reduction of runoff flow that can transport other dissolved pollutants. These findings were insensitive to filter vegetation type. Thus, introduction of improved ISOS is desirable while VFS may be targeted to specific hot spots within the irrigation district. This study shows that the adoption of dense vegetation buffers in vulnerable semi-arid irrigated regions can be effective to mitigate agricultural impacts and provide environmental protection. However, it should not be adopted as an alternative to proper on-site irrigation practices, rather as a complementary off-site pollution control practice.

Highlights (for review)

- Vegetative buffers on tail furrows mitigate sediment delivery.
- Irrigation management changes reduce both runoff and sediment delivery.
- Changes of irrigation management faces initial adoption limitations.
- Volume of runoff and slope are the main factors controlling erosion.
- Reduction of runoff and sediment is insensitive to the vegetation types tested

Title

Watering or buffering? Runoff and sediment pollution control from furrow irrigated fields in arid environments

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Abstract

Surface irrigated agriculture in arid and semi-arid regions contributes to downstream environmental degradation. Changes in irrigation system operational scenarios (ISOS) can represent an economic alternative to reduce surface runoff impacts. At the same time the use of vegetative filter strips (VFS) can have a positive impact on the ecological health of rural landscapes by reducing erosion, improving water quality, increasing biodiversity, and expanding wildlife habitat. The goal of this paper is, using a combination of field data and mechanistic modeling results, to evaluate and compare the spatial effectiveness of improvements in ISOS and introduction of VFS to reduce surface runoff pollution in the semi-arid/arid furrow irrigation agroecosystem that exceeds current regulatory turbidity limits (25 NTU). Five main factor interactions were studied: four soil textures, two field slopes, three ISOS, six filter vegetation types, and ten filter lengths. Slope and runoff volume were identified as the two main drivers of sediment export from furrows. Shifting from current ISOS to less water consumptive irrigation practices reduce runoff in addition to sediment delivery to comply with environmental regulations. The implementation of 3 to 9 m vegetative buffers on experimental parcels were found to mitigate sediment delivery (greater than 90% sediment reduction) on tail drainage ditches but had limited effect in the reduction of runoff flow that can transport other dissolved pollutants. These findings were insensitive to filter vegetation type. Thus, introduction of improved ISOS is desirable while VFS may be targeted to specific hot spots within the irrigation district. This study shows that the adoption of dense vegetation buffers in vulnerable semi-arid irrigated regions can be effective to mitigate agricultural impacts and provide environmental protection. However, it should not be adopted as an alternative to proper on-site irrigation practices, rather as a complementary off-site pollution control practice.

Key words: furrow irrigation, rill irrigation, total suspended solids, vegetative filter strips, VFSMOD, water management, hotspots, targeting, best management practices

1. Introduction

Irrigated agriculture in arid and semi-arid regions offers the advantage that in these settings crops tend to achieve exceptionally high photosynthetic efficiency (Sojka *et al.*, 2007). At the same time, irrigation in semi-arid environments represents one of the most serious challenges to sustainable agriculture. Semi-arid, irrigated agriculture is conducted largely on shallow soils vulnerable to irrigation-induced erosion (Sojka *et al.*, 2007), contributing to water quality degradation for downstream users. The issue is exacerbated by large concentrated flows applied under surface irrigation management, and in particular under furrow irrigation (also referred to as rill irrigation), where water application efficiency rarely achieves more than 60% and tailwater runoff results in major water and sediment losses (Koluvek *et al.*, 1993). Currently, 45% of the United States' 22 million hectares irrigated croplands are under surface irrigation, of which about half is furrow irrigated (USDA, 2009). Thus, to meet water quality standards and to protect natural ecosystems there is a pressing need to substantially improve water quality in furrow irrigation return flows (Szogi *et al.*, 2007).

Among best management practices (BMP), vegetative filter strips (VFS) represent an efficient and economical way to reduce agricultural nonpoint source pollution, reduce runoff and remove suspended solids, nutrients and pesticides from runoff (e.g. Barfield *et al.*, 1978; Muscutt *et al.*, 1993; Qiu and Dosskey, 2012). Dense vegetation in VFS acts as a filter by increasing surface roughness and augmenting infiltration that decreases flow volumes and velocity. This reduces the transport capacity of flow and encourages sediment deposition in the VFS (Barfield *et al.*, 1978; Foster, 1982; Rose *et al.*, 2002). These processes have a direct impact on sediment-bound nutrient transport and an indirect impact on soluble compounds by increasing infiltration (Kuo and Muñoz-Carpena, 2009). Lovell and Sullival (2006) point out that VFS can have a positive impact on the ecological health of rural landscapes by reducing erosion, improving water quality, increasing biodiversity, and expanding wildlife habitat. However, VFS efficiency depends on several external and internal factors such as: incoming runoff volume, discharge, soil properties, filter sizes, and vegetation characteristics (e.g. Barfield *et al.*, 1978; Muñoz-Carpena *et al.*, 1993a; Vought *et al.*, 1995). Several researchers have used this knowledge to model and analyze the characteristics and efficiency of VFS in humid and sub-humid agricultural watersheds. For example, Dosskey *et al.* (2008), presents a design aid for determining width of VFS under Hortonian runoff based on a process-based Vegetative Filter Strip Model (VFSMOD, Muñoz-Carpena and Parsons, 2011). Moreover, to help optimize the placement of VFS within watersheds, Dosskey *et al.* (2011) developed a spatial index based on VFSMOD that related runoff source area to different locations. White and Arnold (2009) also developed a revised algorithm for VFS efficiency for the watershed model SWAT based on results from VFSMOD simulations for a wide range of conditions. Research on modeling surface irrigation in arid/semi-arid regions has primarily focused on simulating the furrow system (e.g. Nearing *et al.*, 1989; Bautista *et al.*, 2009). To our knowledge, no research has addressed the pollution control through vegetative buffers at the end of furrow irrigated fields or the coupling of furrow irrigation and VFS systems using a mechanistic approach.

This study explores the operation improvement of the furrow irrigation system and the novel implementation of VFSs in arid environments as a BMP to control sediment transport in the Yakima River Basin, central Washington State. Granger Drain (Fig. 1) is a tributary to the lower Yakima River that has historically contributed high sediment loads that exceed suspended sediment water quality standards (Joy and Patterson, 1997). While VFSs are typically used to mitigate storm runoff in humid regions, this semi-arid region receives a mean annual precipitation of 150 mm (~5 in.) and sediment transport is largely governed by off-field movement of irrigation water (Fuhrer *et al*. 2004). One third of the parcels in Granger Drain use furrow irrigation, as this is a simple and cost-effective irrigation method. Water turbidity (NTU), used as a surrogate of total suspended sediments, at the Granger drain outlet exceeds the recommended values (25 NTU turbidity, Fig. 2) approximately 60% of the time based on criteria to protect aquatic life (Sigler *et al.*, 1984). Elevated turbidity levels are synchronized with the irrigation season (April-October, Fig. 2) (Tooley, 1995), creating a need to evaluate BMPs to mitigate water quality impairments imparted by irrigation practices, such as changes in irrigation system operational scenarios (ISOS) and the implementation of VFS.

The goal of this paper is to utilize a combination of field data from a semi-arid/arid furrow irrigation region and deterministic mechanistic modeling under a wide range of field conditions to evaluate the water quality improvement of vegetative buffers, and compare these with several irrigation system operational scenarios proposed for the area. This experimental/modeling approach allows for the evaluation of alternative irrigation management schemes and the identification of buffer placement and optimal design characteristics to reduce extant surface water pollution. The specific objectives are to: (i) describe the water and sediment flow through in-field furrows and buffers to determine the potential reduction at the edge of the parcel; and (ii) conduct a spatially-distributed analysis of changes in ISOS and optimal buffer targeting and implementation, and compare the results.

2. Material and methods

2.1. Study area

This study was conducted in the Granger Drain (Fig. 1) within the Yakima River basin, located in Washington State, USA. The Granger Drain is a small agricultural watershed comprising 7,500 ha distributed among 1,540 parcels located in the jurisdiction of the Roza and Sunnyside Valley Irrigation Districts. Furrow irrigated parcels represent close to one third of the total, represented by 409 parcels (2,100 ha). The remaining parcels use sprinkler and drip irrigation systems, which generally contribute a negligible amount of the surface runoff collected at the irrigation return ditches (Fuhrer *et al.*, 2004). The climate in the area is cold semi-arid (Bsk) according to the Koppen-Geiger climate classification (Rubel and Kottek, 2010). The average annual precipitation during 1999-2012 was 150 mm, with the lowest monthly average precipitation (4 mm) in August and the highest (26 mm) in December. For the period of record 1999-2010, the average minimum and maximum monthly temperatures were 0.0 ºC (December) and 23.1 ºC (July), respectively.

Based on the surface soil texture class identified in the SSURGO database (Soil Survey Staff, 2014), there are four predominant soil texture classes on the furrow-irrigated parcels (Table 1): loamy sand (3%), sandy loam (17%), loam (1%) and silty loam (79%). Furrow irrigated parcels have average slopes down-furrow ranging from 0.5% to 2%, and have an average length of 200 m (600 feet). The geometry of a typical furrow cross-section is trapezoidal with 0.12 m of bottom width, 45º slope side-walls and 0.76 m distance between furrow axes (Bodah *et al.*, 2012; Bodah, 2013). Irrigation is generally carried out by continuous pulses of water of 12 hours of duration (Fuhrer *et al.*, 2004). There is variation in how producers set up siphon tubes between the supply canal and the field; a typical example is the use of two siphon tubes (corrugated polyethylene pipe) of diameter 32 mm (1 1/4") and around 2 m of length for each furrow. The average vertical distance between the siphon tube opening (in supply canal) and siphon tube outflow (in furrow) is 0.15 m, which typically delivers to the furrow a water irrigation rate of 0.6 L s^{-1}. Water exits the furrows at the bottom of the field, and the return flows are collected in a second open channel (tail ditch). The water in the tail ditch is routed to a drain that feeds into the regional drainage network and discharges to the Yakima River (Fig. 1).

2.2. Field experiments

VFS were established at the edge of two furrow-irrigated parcels in the study area, which were monitored during 2011 and 2012 (Bodah *et al.*, 2012; Bodah, 2013). Parcel #1 consisted of a 240 m long furrow field with a consistent 0.17% slope. The soil had a loamy texture class. Parcel #2 consisted of a 183 m long furrow field with a variable slope. The first 55 m of the field had a 3% slope, the following 73 m had a 5% slope, and the final 55 m had a 1.5% slope. The soil had a texture class on the border of sandy loam to loam, so for simulations it was assigned sandy loam parameters. In both parcels the row-crop was grain corn and irrigation water was delivered to the furrow at a rate of 0.6 L s^{-1} for 12 hours, following the method described on the previous section. VFS were established on 12 replicated 9.14 m by 9.14 m plots. Each plot was then divided by berms into three sub-plots, each measuring 3.05 m wide. In order to facilitate evaluation of filter strip length effects, the sub-plots had VFS lengths of 9.14 m, 6.10 m and 3.05m. Four different VFS vegetation types were included: Baronesse barley (*Hordeum vulgare*), alfalfa (*medicago sativa*), Bromar mountain bromegrass (*Bromus marginatus*) and Rosana western wheatgrass (*Pascopyrum smithii*). During each scheduled irrigation event, water samples (500 mL) and rates were collected at the furrow tail for time intervals of 0, 15, 30, 45, 60, 90, 120, and 180 minutes after the first flow was observed visually. VFS inflow and outflow volume measurements were recorded from marked fiberglass flumes at the time of each sampling event. In the event that a plot had more than one point of inflow (more than one active furrow), the volume of each actively flowing furrow was summed and recorded. However, water samples were only collected from one active furrow per subplot. Sediment load was determined by passing a portion of each sample through a Pall type A/E 47mm glass fiber filter in conjunction with a vacuum filtration system. 114 and 20 irrigation events were recorded on parcel #1 and #2, respectively. These two parcels were used for model evaluation.

2.3. Description of models

In this study, the furrow-VFS system is analyzed by coupling physical models (Fig. 3). Water flow and associated erosion was first simulated in field furrows, and subsequently the output from this first subsystem was simulated through the VFS.

In the furrow subsystem, irrigation water flow was simulated by using the physical model WinSRFR 4.1.2 (Bautista *et al.*, 2009) that performs the unsteady flow hydraulic analysis of surface irrigation systems. Users can analyze field evaluation data, estimate the field infiltration properties, assess the performance of an observed irrigation event, suggest design and operational alternatives, test individual scenarios, and conduct sensitivity analyses. WinSRFR internally selects a zero-inertia or kinematic wave model based on slope and boundary conditions. Water infiltration is calculated with the empirical Kostiakov formula (Kostiakov, 1932; Bautista *et al.*, 2009).

$$z=kt^a \quad (1)$$

where z is the infiltrated depth (mm) computed as a function of the intake opportunity time t (h), k is a coefficient constant representing the relative ease at which water infiltrates into the soil (mm h^{-a}), a is an exponential constant describing the change in infiltration rate as the soil saturates with water. For each soil texture, the empirical Kostiakov parameters were estimated by least-squares fitting eq. (1) to Green-Ampt infiltration results (0 to 15 hours in 0.1 hour increments) parameterized based on Rawls *et al.* (1983). This approach offers physical consistency between the infiltration components used in the parcel (WinSRFR) and the VFS (VFSMOD that uses Green-Ampt infiltration, described later) (Table 1). Results from the one-dimensional infiltration eq. (1) are used to calculate two-dimensional furrow infiltration based on WinSRFR approaches (Bautista *et al.*, 2009). In order to take into account the effect of variable depth of flow along the length of run, the local wetted perimeter option offered by WinSRFR was selected. Under the proposed approach, infiltration could be underestimated since infiltration by absorption is not considered (Fok and Chiang, 1984; Skonard and Martin, 2002; Bautista *et al.*, 2014). For the WinSRFR simulations other option is trapezoidal furrow geometry. In all simulations, furrows are considered as bare soil using a standard value of Manning's surface roughness (0.04).

Because this study was focused on the exported sediments and flow at the furrow end, the output hydrograph from WinSRFR was used to estimate soil water erosion. For this purpose, the widely used formulation of concentrated water flow erosion (Foster and Meyer, (1972) was used in this study. This has been implemented in the WEPP erosion model (Nearing *et al.*, 1989; Laflen *et al.*, 1991) and tested on furrow irrigation studies (e.g. Trout and Neibling, 1993; Fernández-Gómez *et al.*, 2004). This approach implies that for small time steps, the properties of the system can be assumed to change little within each time step (piecemeal quasi-steady conditions). Thus, furrow erosion calculations can be made on discrete time steps along the hydrograph curve, reproducing dynamic results. The furrow soil erosion processes comprise soil detachment, transport, and deposition in the furrow. The sediment load in the furrow per unit width (G, kg s^{-1} m^{-1}) along the furrow (x, m) is calculated for each time step via the following equation:

$$dG/dx=D[1-(G/T)] \quad (2)$$

where, D is flow detachment capacity (kg s^{-1} m^{-2}), T is flow transport capacity in the furrow (kg s^{-1} m^{-1}). Integrating along the furrow length (L, m), the instantaneous sediment load at the furrow end per unit width is estimated by:

$$G=T\{1-\exp[(D/T)L]\} \quad (3)$$

The equation was implemented in Matlab software (v2013a, The MathWorks, Inc., USA) by numerical integration along the WinSRFR output hydrograph at the end of the furrow. Detachment capacity is a linear function of hydraulic shear stress and is calculated as follows:

$$D=K(\tau-\tau_c) \quad (4)$$

where, K is soil erodibility (s m^{-1}), τ is hydraulic shear stress of flowing water (Pa) and τ_c is the soil critical shear stress (Pa). In this study, K and τ_c values are estimated for each soil textural class based on the empirical relationship proposed by Elliot *et al.* (1989), which is used in the WEPP model. However, Bjorneberg *et al.* (1999) pointed out that τ_c reported by Elliot *et al.* (1989) often over-predicts soil erosion on furrow-induced erosion and recommended using one order of magnitude less than the previous values. In fact, Kemper *et al.* (1985) noted that critical shear stress for furrow irrigated soils is essentially zero. Although we recognize the uncertainty on both parameter estimations, we considered these values as first approximations based on the limited experimental data, where the values selected for K and τ_c (Table 1) fall within the ranges of values reported in the literature for concentrated flow erosion (Knapen *et al.*, 2007). These parameters are discussed further in the results section.

Hydraulic shear stress is calculated by the following equation (Foster, 1982):

$$\tau = \gamma h \cdot S(n_b/n_c)^{0.9} \quad (5)$$

where, γ is the specific weight of water (9,800 N m^{-3}), h is the water depth (m), S is the hydraulic gradient (assumed to be equal to the furrow slope), n_b and n_c are Manning's roughness coefficients for bare soil and rough or vegetated surfaces, respectively. We estimated h using Manning's equation following the same procedure of the WEPP model (Elliott *et al.*, 1989). Values of 0.04 for n_b and 0.1 for n_c were used based on Trout and Neibling (1993) values for irrigated furrow erosion.

Transport capacity in the furrow (eq. 2) was then calculated by a simplified form of the Yalin (1963) transport equation, reported by Foster and Meyer (1972):

$$T = K_t \tau^{(3/2)} \quad (6)$$

K_t is an empirical transport coefficient (m$^{0.5}$ s^2 kg^{-2}). In WEPP K_t is calibrated from the transport capacity, calculated by a modified Yalin equation at the end of a uniform slope using a method described by Finkner *et al.* (1989). K_t becomes relatively constant at higher values of τ, e.g. for a typical silty-loam soil K_t =0.045 for τ>5 Pa (Fig. 2 in Finkner *et al.*, 1989). However, Bjorneberg *et al.* (1999) pointed out that the K_t appeared to be grossly over-predicted in furrows using this method. Thus, on this study a value of K_t = 0.01 was used as a first approximation based on the field experimental data.

Water and sediment values exported from the furrow subsystem were used as inputs for the VFS subsystem (Fig. 3). For each water irrigation event the resulting hydrograph and sedimentograph at the parcel end was routed over the VFS using the physical model VFSMOD (Muñoz-Carpena and Parsons, 2004). VFSMOD is a field-scale, single-event model that is based on flow hydraulics and sediment transport and deposition processes (Muñoz-Carpena *et al.*, 1993b; Muñoz-Carpena *et al.*, 1999). It simulates both field runoff delivery and filter strip retention of sediment and water. Runoff and water infiltration is calculated based on finite element solution of the kinematic wave equation (Muñoz-Carpena *et al.*, 1993a) and the implicit solution (Newton-Raphson) of the extended Green-Ampt equation for unsteady rainfall (Muñoz-Carpena *et al.*, 1993b), respectively. Sediment deposition is calculated by the University of Kentucky model (Barfield *et al.*, 1978; Muñoz-Carpena *et al.*, 1999) developed for VFS, which considers both coarse (bed load) and fine particles (suspended sediments). Thus, VFSMOD is able to simulate complex input hydrographs and sedimentographs considering different VFS, weather and soil characteristics. Researchers have successfully tested the model in a variety of field experiments with good agreement between model predictions and measured values of infiltration, outflow, and trapping efficiency for sediment particles (Muñoz-Carpena *et al.*, 1999; Abu-Zreig, 2001; Han *et al.*, 2005), phosphorus (particulate and dissolved) (Kuo and Muñoz-Carpena, 2009), and pesticides (Sabbagh *et al.*, 2009; Poletika *et al.*, 2009).

VFSMOD is currently used in conjunction with other watershed tools and models to develop criteria and response curves to assess buffer performance and placement at the watershed level (Yang and Weersink, 2004; Dosskey *et al.*, 2005; Dosskey *et al.*, 2006; Dosskey *et al.*, 2008; White and Arnold, 2009; Tomer *et al.*, 2009).

2.4. Analysis of the irrigation district runoff and sediment outflows and control strategies

Typical average seasonal crop irrigation requirements for the main crops in the area (asparagus, corn, grapes, tree fruit and forage) are in the range of 600-1080 mm (USDA-NRCS, 1985), on average 870 mm. Our simulations considered three ISOS present in the area that meet (exceed) the crop water requirements. These ISOS provide the basis for the main objective of this study, i.e. to evaluate the potential surface water quality improvements in the area through a combination of these ISOS and/or an off-site pollution control practice (VFS). The first ISOS represents a typical irrigation practice used by growers in the region consists of delivering 0.6 L s^{-1} of water for 12 hours, denoted here as *actual*. This represents an average depth of applied water of 171 mm per irrigation and the average depth of infiltrated water per irrigation events is around 75 mm per irrigation, which equivalent to 1125 mm of infiltration for an average of 15 irrigations per season). However, water applied following this ISOS exceeds the technical recommendations of 0.3 L s^{-1} for the same study area (Ley and Leib, 2003), hereafter called the *recommended* scenario (average depth of 85 mm and 60 mm for applied and infiltrated water per irrigation, respectively, and equivalent to 900 mm per season). This furrow discharge is based on the USDA-NRCS (1997) recommendation for a non-erosive stream on moderately erodible soils, where the recommended maximum allowable stream discharge per furrow (Q, gpm) is Q=10/S, where S is the slope in percent. Therefore, for steepest parcels (2%) in the study area the maximum allowable stream size is 5 gpm (0.3 l/s). We also considered an intermediate ISOS, hereafter called the *cutback* scenario, consisting of two pulses of 6 hours where 0.6 L s^{-1} is applied for the first 6 hours of irrigation and reduced to 0.3 L s^{-1} for the following 6 hours (average depth of 128 mm and 70 mm for applied and infiltrated water per irrigation, respectively, and equivalent to 1050 mm per season). The *cutback* ISOS can be achieved readily since producers often use two siphon tubes per furrow, so two siphon tubes can be used for the first 6 hours after which one tube is removed for the remainder of the irrigation event.

A variety of recommended VFS vegetation types (Haan *et al.*, 1994) were considered in this study, including ryegrass (*Lolium multiflorum*), tall fescue (*Festuca arundinacea*), bermuda grass (*Cynodon dactylon*) and kentucky bluegrass (*Poa prantensis*) (Table 2), which have similar physical properties than VFS vegetation planted on the experimental plots. We also included alfalfa (*medicago sativa*) and sorghum (*Sorghum x drummondi*) that although not typically recommended for VFS can represent potential extra income if harvested. It is worth mentioning that although these plants are not native, they can be established successfully under these arid conditions if supplementary irrigation is applied during the crucial establishment phase (germination and seedling) (Bodah, 2013). During the summer, when evapotranspiration is at a maximum and precipitation is negligible, the VFS receives enough water from the irrigation return flows exiting the field to support vegetation maintenance (Bodah, 2013). Finally, the VFS lengths considered in the modeling study range from 5 m to 50 m, in increments of 5 m (10 lengths).

Thus, this analysis included a wide range of conditions. Overall, 1,400 combinations were assessed comprised of the 5 factors considered: soil texture (4), parcel slope (2), ISOS (3), VFS vegetation (6) and VFS length (10).

3. Results and discussion

3.1. Field experiments and model testing: runoff and soil erosion

Fig. 4 shows the observed and simulated data for the two monitored parcels. The observed average runoff volume and soil loss per furrow and irrigation event (first 3 hours of observed flow) was in parcel #1 1.99 m^3 and 0.07 kg, and in parcel #2 1.17 m^3 and 6.30 kg. The simulated irrigation events for both parcels delivered runoff and soil erosion values per event (first 3 hours of flow) of 2.20 m^3 and 0.00 kg, and 3.45 m^3 and 8.01 kg, respectively. In all cases, the simulated values are in the range of the observed field data. Simulated runoff is slightly higher in parcel #2 than in parcel #1. This is due to the fact that the input flow discharges are identical in both parcels and the furrows in parcel #2 are shorter and steeper than in parcel #1. Using the selected parameters for the erosion model, the simulated soil loss produced similar values to the observed average values for both parcels. Sediment retention in the VFS for all simulations, using VFS lengths of 3 m, 6 m and 9 m were higher than 90%, which are in agreement with recorded field data (Bodah *et al.*, 2012; Bodah, 2013).

3.2. Field flow and sediment dynamics and outflows

Fig. 5a depicts WinSRFR hydraulic summaries of the three irrigation scenarios for two soil textural classes (loamy sand and silty loam) and two furrow slopes (0.5% and 2%). On the steeper parcels (slope 2%) under the *actual* ISOS, a constant inflow rate of 0.6 L s^{-1} for 12 hours produces the highest runoff delivery rate with a maximum instantaneous value of 0.31 L s^{-1} on the loamy sand soil and 0.50 L s^{-1} in the silty loam. In both cases, the *recommended* irrigation inflow of 0.3 L s^{-1} for 12 hours generates the least amount of runoff, with a maximum instantaneous runoff of 0.04 L s^{-1} and 0.21 L s^{-1} for loamy sand and silty loam, respectively. So, under *actual* ISOS, on the steeper parcels, the runoff volume represents 45% and 75% of the total irrigation water used, for loamy sand and silty loam, respectively. For the steeper parcels and *actual* ISOS irrigation, water reaches the furrow end (200 m) around 0.4 hours after starting irrigation. Under this condition, where a 0.6 L s^{-1} input flow is applied, time advances are similar for the different soil textures. This rate is in agreement with field observations (Bodah *et al.*, 2012). However, if the inflow rate is reduced to correspond with the *recommended* ISOS (0.3 L s^{-1}), water advance time increases over different textural soil classes from 1.1 hours (silty loam) to 4.2 hours (loamy sand). On the other hand, on parcels exhibiting a 0.5% slope and *actual* ISOS the generated peak runoff ranged from 0.26 L s^{-1} to 0.43 L s^{-1}, for loamy sand and silty loam, respectively. Under the *recommended* ISOS, runoff values drop to 0 L s^{-1} and 0.20 L s^{-1}. At the same time, the advance time on these more leveled parcels increases to around 0.7 hours for all texture soils under *actual* ISOS. If the *recommended* scenario is simulated on the 0.5% slope parcels the advance time rises to 1.6 hours and 11.4 hours for silty loam and loamy sand, respectively. These values are similar to values reported in field surveys for surface irrigation (e.g. Bjorneberg *et al.*, 2006; Mailapalli *et al.*, 2009). Additionally, under *actual* ISOS the runoff volume decreases to 35% and 60% of total irrigation water used for loamy sand and silty loam, respectively. These values decreased significantly under *recommended* ISOS simulations, dropping to 0% and 50%.

Erosion rates were calculated based on the hydrographs generated for the combination of the following factors: soil texture, parcel slope and ISOS. Estimated soil loss by furrow irrigation ranges from 0 to 6 Mg ha^{-1} on average (Fig. 6), values in agreement with the literature. For example, Fernández-Gómez *et al.* (2004) obtained values at the end of 200-m furrows in the range of 0 to 10 Mg ha^{-1} on loamy and clay loam soils with a furrow slope of 0.8% and an inflow rate of 1.7 L s^{-1}. These values represent end of the furrow conditions, where values along the furrow can be highly variable (Trout, 1996). Maximum erosion rates are typically found at the beginning of the furrow where the flow is at a maximum and the sediment load is at a minimum since the incoming irrigation water is usually low in suspended solids. Although the spatial variability of water erosion along the furrow is important, here we are focused on the sediment load export from furrows.

The soil loss tolerance, defined as the maximum amount of erosion at which the soil quality is maintained, can be estimated for our study area using the USDA NRCS (2013) criteria as ~12 Mg ha^{-1} yr^{-1}. Therefore, assuming typical average requirements of 15 irrigation events per season, the average soil loss tolerance per irrigation event would be about 1 Mg ha^{-1}. This value is exceeded in all simulations using a 2% slope and *actual* ISOS (Fig. 6). In soils with lower infiltration capacity, such as the silty loam and loam soils that represent 80% of the study area, a potential change in irrigation management could reduce soil loss rates below the tolerance limit. By contrast, all of the simulated combinations with 0.5% slope are around or lower this tolerance threshold.

Finally, it should be noted that as Li and Zhang (2010) indicated, soil loss is positively correlated with the volume of runoff and the slope of the furrow (R^2 = 0.97 for slope 2% and R^2 = 0.93 for slope 0.5%) (Fig. 6). Consequently, since slope is a condition difficult to modify in our study area, the volume of runoff controlled by ISOS is the main factor controlling furrow erosion.

3.3. Runoff reduction efficiencies with water management and VFS

The exported hydrographs and sedimentographs from the furrow subsystem were used as inputs for the VFSMOD simulations in the subsequent VFS subsystem. Runoff and sediment reduction (*R*) for the steepest parcels (slope 2%) and different VFS lengths (VL) are presented in Fig. 7. As proposed by Dosskey *et al.* (2008), the runoff and sediment reduction follow a near-perfect relationship ($R^2 > 0.95$) given by,

$$R(\%) = (1-\alpha)\,[1-\exp(-\beta \cdot VL)] \qquad (7)$$

where, α and β are calibration coefficients.

These relationships can be used as a design aid for determining appropriate VFS length to achieve specific pollution reduction goals (Muñoz-Carpena and Parsons, 2004). Thus, once the desired level of trapping efficiency is selected, both for runoff or/and sediment, the optimal VFS length to achieve that level of reduction can be obtained by intersecting the response curves (Fig. 7) for the specific field conditions (soil, slope, irrigation).

The results show that in terms of runoff reduction (and associated dissolved pollutants) VFS implementation can achieve similar results as those found for a change in ISOS without VFS. For example, considering the 2%-sloped parcels with high infiltration capacity soils (i.e., loamy sand) and applying *actual* ISOS as the reference value, a shift in ISOS from *actual* to *cutback* ISOS implies a runoff reduction of 45%. Using the same conditions, if ISOS is changed from *actual* to *recommended* the water runoff is reduced to 94%. On the other hand, similar runoff reductions can be achieved by the implementation of a VFS without changing the ISOS (Fig. 7a). Thus, under *actual* ISOS and implementing a 15-m length VFS the water runoff is reduced to 48% (Fig. 7a). To achieve the same runoff reduction by changing from *actual* to *recommended* ISOS, a VFS of 30 m should be implemented (Fig. 7a). For the 2%-sloped parcels without VFS and soil with less infiltration capacity (e.g., silty loam), the water runoff reduction from *actual* to *cutback* and *recommended* ISOS represents a drop of 33% and 63%, respectively. In this case, under *actual* ISOS, an implementation of a 50-m VFS without shifting ISOS reduces runoff by 27% (Fig. 7a). Therefore, under these conditions a change from *actual* to *cutback* ISOS scenario delivers a higher reduction of runoff than the implementation of a 50-m VFS.

Fig. 7b presents the reduction of sediment after implementation of VFS lengths under different ISOS scenarios. Similar to the results found for runoff, there is a greater reduction in sediments on soils with higher infiltration capacity since the flow transport capacity decreases when flow velocity decreases (Barfield *et al.*, 1978; Muñoz-Carpena *et al.*, 1999; Borin *et al.*, 2005). In all cases, sediment load is reduced by over 90% with VFS lengths equal to or greater than 15 m. Similar results were shown by Duchemin and Hogue (2009); implementation of a 5-m VFS length on a 3% slope parcel of silty loam soil yielded 87% reduction of total suspended sediments (a surrogate variable of sediment load). However, changing *actual* ISOS to either *cutback* or *recommended* ISOS without implementing a VFS reduces sediment loads, but not always to the 90% of sediment reduction level described above. For example, if *actual* ISOS is shifted to *cutback* or *recommended* ISOS without the implementation of a VFS the exported sediment is reduced by 48% and 92%, respectively, on 2%-sloped parcels with high infiltration capacity soils (e.g., loamy sand). For parcels on a 2% slope with soils exhibiting less infiltration capacity (e.g., silty loam) sediment reductions due to changes in ISOS from *actual* to *cutback* or *recommend* were 30% and 60%, respectively, when no VFS is implemented.

Both field and simulated results showed that runoff and sediment reduction is insensitive to the vegetation types analyzed in the study (Table 2), all of which yielded similar results. This is related to the low density of plants (vegetation spacing) in the VFS analyzed. When Muñoz-Carpena *et al.* (1999) investigated the effect of vegetation spacing (0.5-10 cm) on trapping various incoming sediment particle classes (clay, silt, small aggregates, large aggregates and sand) on a fixed filter length, they found that sediment removal was not effective for vegetation spacing greater that 2.2 cm for particle sizes other than sand.

3.4. Spatial analysis of alternative targeted BMPs

Finally, in order to explore alternative BMP scenarios, Fig. 8 presents the spatial distribution of water runoff (top row) and sediment delivery (bottom row) by Granger Drain parcel under different management scenarios. The first column of Fig. 8 represents the current reference scenario (i.e., *actual* ISOS and no VFS). Based on previous results, parcels with steeper slopes and heavier soils deliver more water runoff, as well as produce larger soil loss (darker parcels). The center column of Fig. 8 presents the results after modeling the implementation of a VFS of 5 m length and keeping the *actual* ISOS. Under this scenario water runoff and soil loss exported from the parcels are reduced on average 5% and 80%, respectively. For the whole watershed the soil loss per irritation event decreases from the estimated 3.7 Mg ha^{-1} to 1.1 Mg ha^{-1}. As discussed before, this value is close the soil loss tolerance threshold following the USDA NRCS (2013) criteria. The right column of Fig. 8 presents water runoff and soil exported under a change in ISOS from *actual* to *recommended* without the implementation of VFSs. This scenario found that water runoff and soil loss exported from the parcels were reduced on average by 67% and 68%, respectively. In this case, the average soil loss per irrigation event over the furrow irrigated parcels dropped to a value of 1.32 Mg ha^{-1}, which is slightly higher than the acceptable level under the USDA NRCS (2013) criteria.

Importantly, the results show that reducing irrigation to recommended levels simultaneously limits the exported liquid (water, dissolved nutrients and pollutant) and solid (sediments and sediment-bonded pollutants) phases from furrow irrigated parcels. Wide implementation of improved ISOS can face implicit limitations in each scenario. Heterogeneous soil and slopes make irrigation management difficult, and although automation can be applied there are practical limits to what can be achieved (Shahidian *et al.*, 2013). Also, the implementation of improved ISOS can be slow since its introduction requires additional labor and training. Adoption of VFSs may be complementary to meet the turbidity regulatory level, but the field component of this study found that VFS implementation in the overall agricultural management system used in the Yakima Basin can be challenging. Over all scenarios considered, improving ISOS is the most effective means to meet water quality objectives with less of a burden on the growers and could make it a more readily adopted BMP for reducing sediment loads originating from furrow irrigated fields in arid regions (Table 3). Importantly, as an on-site BMP it conserves land and water resources and improves the overall sustainability of the agricultural system. As a complementary off-site practice it is recommended that VFS be considered only for the most problematic parcels in the irrigation district and in conjunction with agricultural producers who are willing to take the necessary land out of production and maintain them so that they act as efficient BMPs. In summary, this study found that improved ISOS should be given priority for implementation.

4. Conclusions

This paper describes a combination of field experiments with a physically-based modeling framework to compare the effectiveness of VFS implementation with improved irrigation system operational strategies under a wide range of field conditions on an arid region furrow irrigation system. The simulated runoff volume and soils loss per furrow and one irrigation event are in the range of the observed field data. The implementation of 3 to 9 m vegetative buffers on experimental parcels were found to mitigate sediment delivery (above 90% of sediment reduction) on tail drainage ditches to comply with environmental regulations. The average soil loss tolerance per irrigation event of ~1 Mg ha^{-1} per irrigation event was found to be exceeded in parcels exhibiting a 2% slope and under *actual* ISOS. By contrast, all of the simulated combinations with 0.5% slope are around or lower than this tolerance threshold. The volume of runoff and the slope of the furrow were found to be the main factors controlling erosion. However, since slope is a condition difficult to modify, the volume of runoff is one of the key features controlling furrow erosion. In soils with lower infiltration capacity, which represent 80% of the study area, a change in ISOS reduces soil loss below the tolerance limit.

An improvement in ISOS by itself without the implementation of VFS significantly reduces both water runoff and sediment loads. A change of ISOS from *actual* to *cutback* ISOS implies a runoff reduction on the range of 33% to 94% and sediment load reduction on the range of 30% to 90%. On the other hand, the implementation of VFS has a positive reduction effect mainly on exported sediment from furrows. In all cases sediment load is reduced by over 90% with VFS lengths equal to or greater than 15 m. The study shows that the reduction of runoff and sediment is insensitive to the vegetation types analyzed in the study. The retention curves developed under different combination of VFS settings can be used as a design aid for determining appropriate VFS length to achieve specific environmental protection goals.

The spatial analysis of all parcels in the irrigation district showed that parcels with a 2% slope and heavier soils deliver more water runoff, as well as produce larger soil loss. However, if a producer shifts from *actual* to *recommended* ISOS without VFS, the water runoff and soil loss exported from the parcels would be reduced on average 67% and 68%, respectively, sufficient to meet the recommended soil loss thresholds. Therefore, based on the results of this study, several measures can be implemented depending on the specific objective pursued by managers. A shift from *actual* ISOS to less water consumptive irrigation practices (e.g., *cutback* and *recommended* ISOS scenarios) is desirable, although such an implementation could face initial barriers (e.g. technological knowledge, heterogeneous soil and slope, and farmer resistance to adoption of new practices due to additional labor/time required). In all, an introduction of improved ISOS may be desirable on larger parcel sections, while VFS may be targeted on specific hot spots in the irrigation district. However, it should be noted that managing VFS at the end of furrow-irrigated fields can also be difficult based on field trials.

As it is common in many studies, the results are restricted by the limited experimental data available (representing ~20% of the soils in study area). The strength of our approach is that we rely on physical modeling instead of empirical relationships to upscale the results from the limited experimental data set. This can reduce the inherent data uncertainties and make the results more tractable compared to simpler empirical analysis. Although the analysis is simplified by a strictly deterministic approach, it is based on a large number of combinations intended to represent a wide range of field conditions (i.e. overall 1,400 combinations were assessed comprised of the 5 factors considered: 4 soil texture, 2 parcel slope, 3 ISOS, 6 VFS vegetation and 10 VFS length). Stochastic variation of the input factors combined with state-of-the-art global sensitivity and uncertainty analysis (Muñoz-Carpena *et al.*, 2006; Shirmohammadi *et al.*, 2006) is a critical element in environmental modeling and should be the subject of future work. Finally, it is worth mentioning that an in-depth study to optimize the irrigation operation should be done in order to conserve the water resource while meeting water crop needs and minimizing environmental impacts.

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References

Abu-Zreig, M., 2001. Factors affecting sediment trapping in vegetated filter strips: simulation study using VFSMOD. Hydrol. Process. 15, 1477-1488.

Barfield, B.J., Tollner, E.W., Hayes, J.C., 1978. The use of grass filters for sediment control in strip mining drainage. Vol. I: Theoretical studies on artificial media. Pub. no. 35-RRR2-78., University of Kentucky, Lexington, KY.

Bautista, E., Clemmens, A.J., Strelkoff, T.S., Schlegel, J., 2009. Modern analysis of surface irrigation systems with WinSRFR. Agric. Water Manage. 96, 1146-1154.

Bautista, E., Warrick, A., Strelkoff, T., 2014. New Results for an Approximate Method for Calculating Two-Dimensional Furrow Infiltration. J. Irrig. Drain. Eng. 140, 04014032.

Bjorneberg, D.L., Trout, T.J., Sojka, R.E., Aase, J.K., 1999. Evaluating Wepp-predicted infiltration, runoff, and soil erosion for furrow irrigation. Trans. ASAE 42, 1733-1741.

Bjorneberg, D., Westermann, D., Aase, J., Clemmens, A., Strelkoff, T., 2006. Sediment and phosphorus transport in irrigation furrows. J. Environ. Qual. 35, 786-794.

Bodah, B.W., 2013. Effective suspended sediment and soluble nutrient load mitigation in irrigated agricultural return flows through the use of vegetative filter strips. Ph.D. thesis. Department of Biological Systems Engineering, Washington State University, Pullman, WA.

Bodah, B.W., Ullman, J.L., Muñoz-Carpena, R., Kiker, G.A., Perez-Ovilla, O., Pan, W.L., Peters, R.T., Stannard, M., 2012. Sediment and nutrient reduction in irrigation return flows by vegetated filter strips on surface irrigated fields. 2012 ASABE Annual International Meeting, Paper #121336855.

Borin, M., Vianello, M., Morari, F., Zanin, G., 2005. Effectiveness of buffer strips in removing pollutants in runoff from a cultivated field in North-East Italy. Agric. Ecosyst. Environ. 105, 101-114.

Chu, S.T., 1978. Infiltration during unsteady rain. Water Resour. Res. 14, 461-466.

Dosskey, M.G., Eisenhauer, D.E., Helmers, M.J., 2005. Establishing conservation buffers using precision information. J. Soil Water Conserv. 60, 349-354.

Dosskey, M.G., Helmers, M.J., Eisenhauer, D.E., 2008. A design aid for determining width of filter strips. J. Soil Water Conserv. 63, 232-241.

Dosskey, M.G., Helmers, M., Eisenhauer, D.E., 2006. An approach for using soil surveys to guide the placement of water quality buffers. J. Soil Water Conserv. 61, 344-354.

Dosskey, M.G., Qiu, Z., Helmers, M.J., Eisenhauer, D.E., 2011. Improved indexes for targeting placement of buffers of Hortonian runoff. J. Soil Water Conserv. 66, 362-372.

Duchemin, M., Hogue, R., 2009. Reduction in agricultural non-point source pollution in the first year following establishment of an integrated grass/tree filter strip system in southern Quebec (Canada). Agric. Ecosyst. Environ. 131, 85-97.

Elliott, W.J., Liebenow, A.M., Laflen, J.M., Kohl, K.D., 1989. A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 & 1988. NSERL Report no. 3.

Fernández-Gómez, R., Mateos, L., Giráldez, J., 2004. Furrow irrigation erosion and management. Irrig. Sci. 23, 123-131.

Finkner, S.C., Nearing, M.A., Foster, G.R., Gilley, J.E., 1989. A simplified equation for modeling sediment transport capacity. Trans. ASAE 32, 1545-1550.

Fok, Y., Chiang, S., 1984. 2-D Infiltration equations for furrow irrigation. J. Irrig. Drain. Eng. 110, 208-217.

Foster, G.R., 1982. Modeling the erosion process. In: Hahn, C.T., Johnson, H.P., Brakensiek, D.L. (Eds.)Hydrologic Modeling of Small Watersheds. American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 297-380.

Foster, G.R., Meyer, L.D., 1972. A closed-form soil erosion equation for upland areas. In: Shen, W.H. (ed.), Sedimentation. Water Resources Publications, Fort Collins, CO, USA.

Fuhrer, G.J., Morace, J.L., Johnson, H.M., Rinella, J.F., Ebbert, J.C., Embrey, S.S., Waite, I.R., Carpenter, K.D., Wise, D.R., Hughes, C.A., 2004. Water quality in the Yakima River Basin, Washington, 1999–2000. U. S. Geological Survey Circular 1237.

Haan, C.T., Barfield, B.J., Hayes, J.C., 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press, New York.

Han, J., Wu, J.S., Allan, C., 2005. Suspended sediment removal by vegetative filter strip treating highway runoff. J. Environ. Sci. Heal. A 40, 1637-1649.

Joy, J., Patterson, B., 1997. A Suspended Sediment and DDT Total Maximum Daily Load Evaluation Report for the Yakima River. Washington State Department of Ecology 97-321.

Kemper, W.D., Trout, T.J., Brown, M.J., Rosenau, R.C., 1985. Furrow erosion and water and soil management. Trans. ASAE 28, 1564-1572.

Knapen, A., Poesen, J., Govers, G., Gyssels, G., Nachtergaele, J., 2007. Resistance of soils to concentrated flow erosion: A review. Earth-Sci. Rev. 80, 75; 109-75; 109.

Koluvek, P.K., Tanji, K.K., Trout, T.J., 1993. Overview of soil-erosion from irrigation. J. Irrig. Drain. E.-ASCE 119, 929-946.

Kostiakov, A.N., 1932. On the dynamics of the coefficient of water percolation in soils and on the necessity for studying it from dynamic point of view for purposes of amelioration. Trans. 6th Comm. Int. Soc. Soil Sci. Part A, 17-21.

Kuo, Y.M., Muñoz-Carpena, R., 2009. Simplified modeling of phosphorus removal by vegetative filter strips to control runoff pollution from phosphate mining areas. J. Hydrol. 378.

Laflen, J.M., Lane, L.J., Foster, G.R., 1991. WEPP: A new Generation of erosion prediction technology. J. Soil Water Conserv. 46, 34-38.

Ley, T.W., Leib, B., 2003. Drought Advisory: Surface Irrigation Systems. EM4828. Washington State University Cooperative Extension. Pullman, WA.

Li, F.H., Zhang, L.J., 2010. Combined Effects of Water Quality and Furrow Gradient on Runoff and Soil Erosion in North China. Pedosphere 20, 35-42.

Lovell, S.T., Sullivan, W.C., 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agric. Ecosyst. Environ. 112, 249-260.

Mailapalli, D.R., Raghuwanshi, N.S., Singh, R., 2009. Sediment transport in furrow irrigation. Irrig. Sci. 27, 449-456.

Muñoz-Carpena, R., Vellidis, G., Shirmohammadi, A., Wallender, W.W., 2006. Evaluation of Modeling Tools for TMDL Development and Implementation. Trans. of ASABE 49(4), 961-965.

Muñoz-Carpena, R., Miller, C.T., Parsons, J.E., 1993a. A Quadratic Petrov-Galerkin solution for kinematic wave overland-flow. Water Resour. Res. 29, 2615-2627.

Muñoz-Carpena, R., Parsons, J.E., 2011. VFSMOD-W Vegetative Filter Strips Modelling System. Model Documentation and User's Manual, University of Florida 6.x.

Muñoz-Carpena, R., Parsons, J.E., Gilliam, J.W., 1999. Modeling hydrology and sediment transport in vegetative filter strips. J. Hydrol. 214, 111-129.

Muñoz-Carpena, R., Parsons, J.E., Gilliam, J.W., 1993b. Numerical approach to the overland-flow process in vegetative filter strips. Trans. ASAE 36, 761-770.

Muñoz-Carpena, R., Parsons, J., 2004. A design procedure for vegetative filter strips using VFSMOD-W. Trans. ASAE 47, 1933-1941.

Muscutt, A.D., Harris, G.L., Bailey, S.W., Davies, D.B., 1993. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agric. Ecosyst. Environ. 45, 59-77.

Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C., 1989. Process-based soil erosion model for USDA-water erosion prediction project technology. Trans. ASAE 32, 1587-1593.

Poletika, N.N., Coody, P.N., Fox, G.A., Sabbagh, G.J., Dolder, S.C., White, J., 2009. Chlorpyrifos and atrazine removal from surface runoff by vegetated filter strips: Runoff experiments and predictive modelling. J. Environ. Qual. 38, 1042-1052.

Qiu, Z., Dosskey, M.G., 2012. Multiple function benefit - Cost comparison of conservation buffer placement strategies. Landscape Urban Plan. 107, 89-99.

Rawls, W.J., Brakensiek, D.L., Miller, N., 1983. Green-Ampt Infiltration Parameters from Soils Data. J. Hydraul. Eng.-ASCE 109, 62-70.

Rose, C.W., Hogarth, W.L., Ghadiri, H., Parlange, J., Okom, A., 2002. Overland flow to and through a segment of uniform resistance. J. Hydrol. 255, 134-150.

Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Koppen-Geiger climate classification. Meteorol. Z. 19, 135-141.

Sabbagh, G.J., Fox, G.A., Kamanzi, A., Roepke, B., Zhang, J.Z., 2009. Effectiveness of vegetative buffer strips in reducing pesticide loading: Quantifying pesticide trapping efficiency. J. Environ. Qual. 38, 762-771.

Shahidian, S., Serralheiro, R.P., Serrano, J.M., 2013. Practical issues in developing a smart surface irrigation system with real-time simulation of furrow advance. Irrig. Drain. 62, 25-36.

Shirmohammadi, A., Chaubey, I., Harmel, R.D., Bosch, D.D., Muñoz-Carpena, R., Dharmasri, C., Sexton, A., Arabi, M., Wolfe, M.L., Frankenberger, J., Graff, C., Sohrabi, T.M., 2006. Uncertainty in TMDL Models. Trans. of ASABE 49(4), 1033-1049.

Sigler, J.W., Bjornn, T.C., Everest, F.H., 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. Trans. Am. Fish. Soc. 113, 142-150.

Skonard, C.J., Martin, D.L., 2002. A Physically Based Two-Dimensional Infiltration Model for Furrow Irrigation. ASAE Paper 022063, ASAE Annual International Meeting / CIGR XVth World Congress.

Soil Survey Staff, 2014. Soil Survey Geographic (SSURGO) Database for [Granger, Washington]. NRCS, USDA. Available online at: http://websoilsurvey.nrcs.usda.gov/. Accesed 05/28/2014.

Sojka, R.E., Bjorneberg, D.L., Trout, T.J., Strelkoff, T.S., Nearing, M.A., 2007. The importance and challenge of modeling irrigation-induced erosion. J. Soil Water Conserv. 62, 153-162.

Szogi, A.A., Leib, B.G., Redulla, C.A., Stevens, R.G., Mathews, G.R., Strausz, D.A., 2007. Erosion control practices integrated with polyacrylamide for nutrient reduction in rill irrigation runoff. Agric. Water Manage. 91, 43-50.

Tomer, M., Dosskey, M., Burkart, M., James, D., Helmers, M., Eisenhauer, D., 2009. Methods to prioritize placement of riparian buffers for improved water quality. Agrofor. Syst. 75, 17-25.

Tooley, J., 1995. GIS Analysis, Yakima River Suspended Sediment TMDL Evaluation. Memorandum to Joe Joy Washington Department of Ecology, Environmental Investigations Program, Olympia, WA 7 pp.

Trout, T.J., Neibling, W.H., 1993. Erosion and sedimentation processes on irrigated fields. J. Irrig. Drain. E.-ASCE 119, 947-963.

Trout, T., 1996. Furrow irrigation erosion and sedimentation: On-field distribution. Trans. ASAE 39, 1717-1723.

USDA, 2009. 2008 Farm and Ranch Irrigation Survey. Vol. 3, Speacial Studies, Part 1, AC-07-SS-1. USDA, Washington, DC.

USDA Natural Resources Conservation Service, 2013. National soil survey handbook, title 430-VI.

USDA-NRCS, 1997. Chapter 6, Irrigation System Design. In: Anonymous National Engineering Handbook, Part 652, Irrigation Design. United State, Department of Agriculture.

USDA-NRCS, 1985. Washington Irrigation Guide Appendix A. WA210-VI-WAIG, 323.

Vought, L.B.M., Pinay, G., Fuglsang, A., Ruffinoni, C., 1995. Structure and function of buffer strips from a water-quality perspective in agricultural landscapes. Landscape Urban Plan. 31, 323-331.

White, M.J., Arnold, J.G., 2009. Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. Hydrol. Process. 23, 1602-1616.

Woolhiser, D.A., Smith, R.E., Goodrich, D.C., 1990. KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual, . USDA-ARS, ARS-Publication no. 77.

Yalin, M.S., 1963. An expression for bed-load transportation. J. Hydraul. Eng.-ASCE 98, 221-250.

Yang, W., Weersink, A., 2004. Cost-effective targeting of riparian buffers. Can. J. Agr. Econ. 52, 17-34.

Figure captions

Figure 1. Granger Drain watershed. The inset map on the bottom right shows the geographic location of the watershed.

Figure 2. Hydrologic summary of Granger Drain watershed at the gauge/monitoring station in Fig. 1. (a) Monthly 25^{th} and 90^{th} percentage of turbidity and discharge, and (b) turbidity exceedance. Turbidity discharge recorded every 15 days, from June of 1997 to October 2012. Daily discharge data from August of 1999 to January of 2013. Data from the Roza-Sunnyside Board of Joint Control.

Figure 3. Schematic representation of the coupled furrow irrigated field and vegetative filter strip systems. From parcel view (left side) to abstraction model description (right side).

Figure 4. Observed and simulated cumulative runoff and soil loss coming off the field (i.e., end of furrow) for the two furrow irrigated parcels.

Figure 5. (a) Furrow hydraulics summary and (b) geometry cross-section. Input and output hydrographs at the furrow are shown in the left and right panels, respectively. Advance and recession irrigation curves along the furrow are presented in the central panel. Simulation on loamy sand soil (gray lines), and silt loam soil (green lines), with a parcel slope of 2%. Irrigation system operational scenarios are displayed with a different line pattern: constant inflow irrigation of 0.3 L s^{-1} per furrow (continuous line, *recommended*), variable irrigation with an initial inflow rate of 0.6 L s^{-1} reduced to 0.3 L s^{-1} after 6 hours (dashed line, *cutback*), and constant irrigation with inflow of 0.6 L s^{-1} per furrow (dotted line, *actual*).

Figure 6. Range of simulated soil loss per irrigation event under different soils, slopes (0.5% and 2%) and irrigation system operational strategies.

Figure 7. (a) Runoff and (b) sediment reduction curves for different vegetative filter strip lengths and average parcel slope of 2%. The simulated values are shown with different symbols depending on the soil texture class and line types for irrigation system operational.

Figure 8. Simulated runoff and sediment released to the irrigation return canal under: (a, b) *actual* irrigation system operational scenario (ISOS) without vegetative filter strips (VFS); (c, d) *actual* ISOS with 5 m of VFS; and (e, f) *recommended* ISOS without VFS.

TABLES

Table 1. Description of surface soil texture class for study parcels used in model simulations. The pressure head at the surface was set as zero in all simulations.

	Soil texture				
Soil characteristics	Loamy sand	Sandy loam	Loam	Silty loam	Source
Saturated hydraulic conductivity, K_s (cm h^{-1})	3.00	2.00	1.32	0.68	SSURGO database (Soil Survey Staff, 2014)
Soil organic matter, *OM* (%)	0.50	2.00	1.50	2.00	SSURGO database (Soil Survey Staff, 2014)
Saturated moisture content, θ_s (-)	0.40	0.45	0.46	0.50	Green-Ampt equation parameters from Rawls *et al.* (1983)
Initial moisture content, θ_i (-)	0.20	0.20	0.15	0.15	Green-Ampt equation parameters from Rawls *et al.* (1983)
Wetting front suction, S_{av} (cm)	5.80	11.00	10.20	19.10	Green-Ampt equation parameters from Rawls *et al.* (1983)
Median particle diameter of the surface soil, d_{50} (mm)	0.135	0.098	0.035	0.018	According to Woolhiser *et al.*(1990), reported by Muñoz-Carpena and Parsons (2011)
Kostiakov's parameter, k (mm h^{-b})	43.50	43.09	42.50	38.50	By fitting eq. (1) to infiltration curves described by Green-Ampt infiltration equation
Kostiakov's exponential parameter, a	0.89	0.80	0.71	0.63	By fitting eq. (1) to infiltration curves described by Green-Ampt infiltration equation
Soil erodibility, K (s m^{-1})	0.018	0.0092	0.0089	0.034	Elliot *et al.* (1989)
Soil critical shear stress, τ_c (Pa)	0.11	0.23	0.27	0.25	Elliot *et al.* (1989) and Bjorneberg e*t al.* (1999)

Table 2. Potential vegetation types considered for vegetative filter strips and related parameters.

Vegetative filter vegetation	*n*	SS (cm)	H (cm)
Alfalfa	0.24	3.02	35
Sorghum	0.24	9.52	20
Ryegrass	0.24	2.15	18
Tall Fescue	0.24	1.63	38
Bermuda Grass	0.24	1.35	25
Kentucky Bluegrass	0.24	1.65	20

Parameter values from Haan *et al*. (1994)
n: Manning's roughness coefficient; *SS*: spacing of the filter media elements; *H*: filter media height.

Table 3. Qualitative cost-benefit comparison of changing irrigation system operational scenario (ISOS) and the implementation of vegetative filter strips (VFS).

Strategy	ΔQ[1]	ΔSed[1]	Implementation Cost	Maintenance Cost	Technical knowledge	Total Score
ISOS	1	1	1	0	0	3
VFS	0	1	0	-1	0	0

[1]ΔQ, ΔSed: Reductions of parcel runoff and sediment; Effects: -1 undesirable, 0 neutral, 1 desirable

Fig 1

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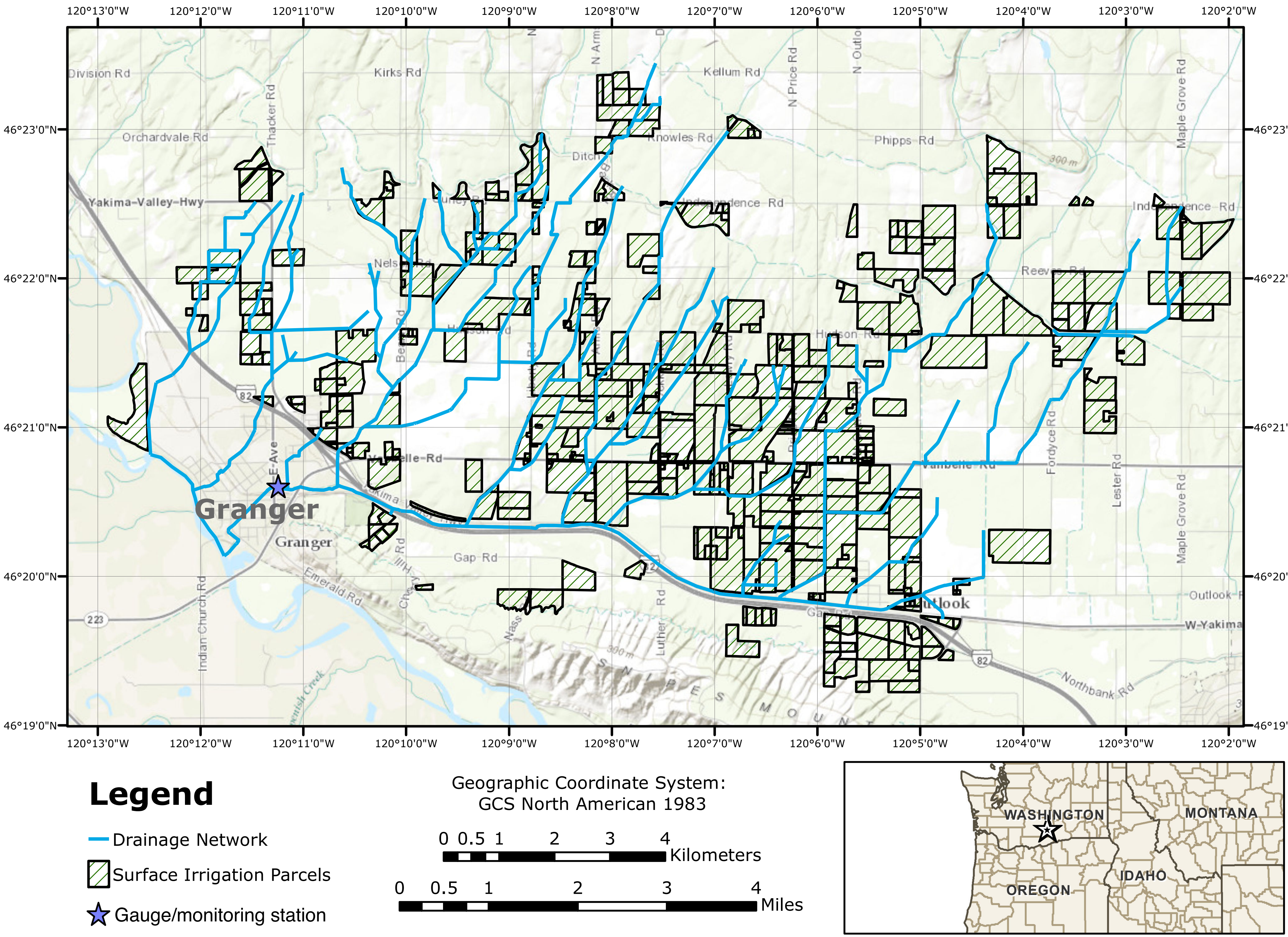

Fig 2

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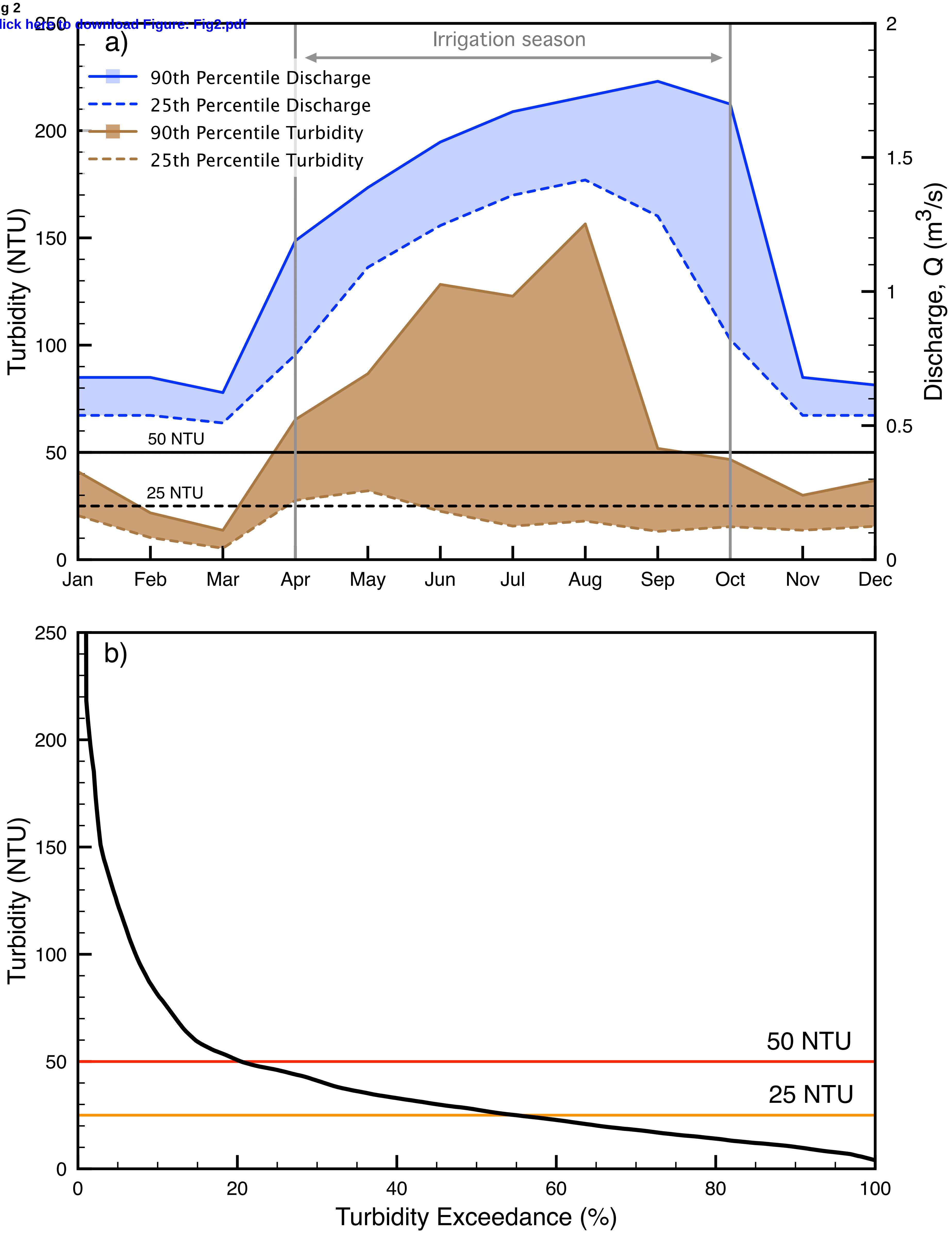

Fig 3

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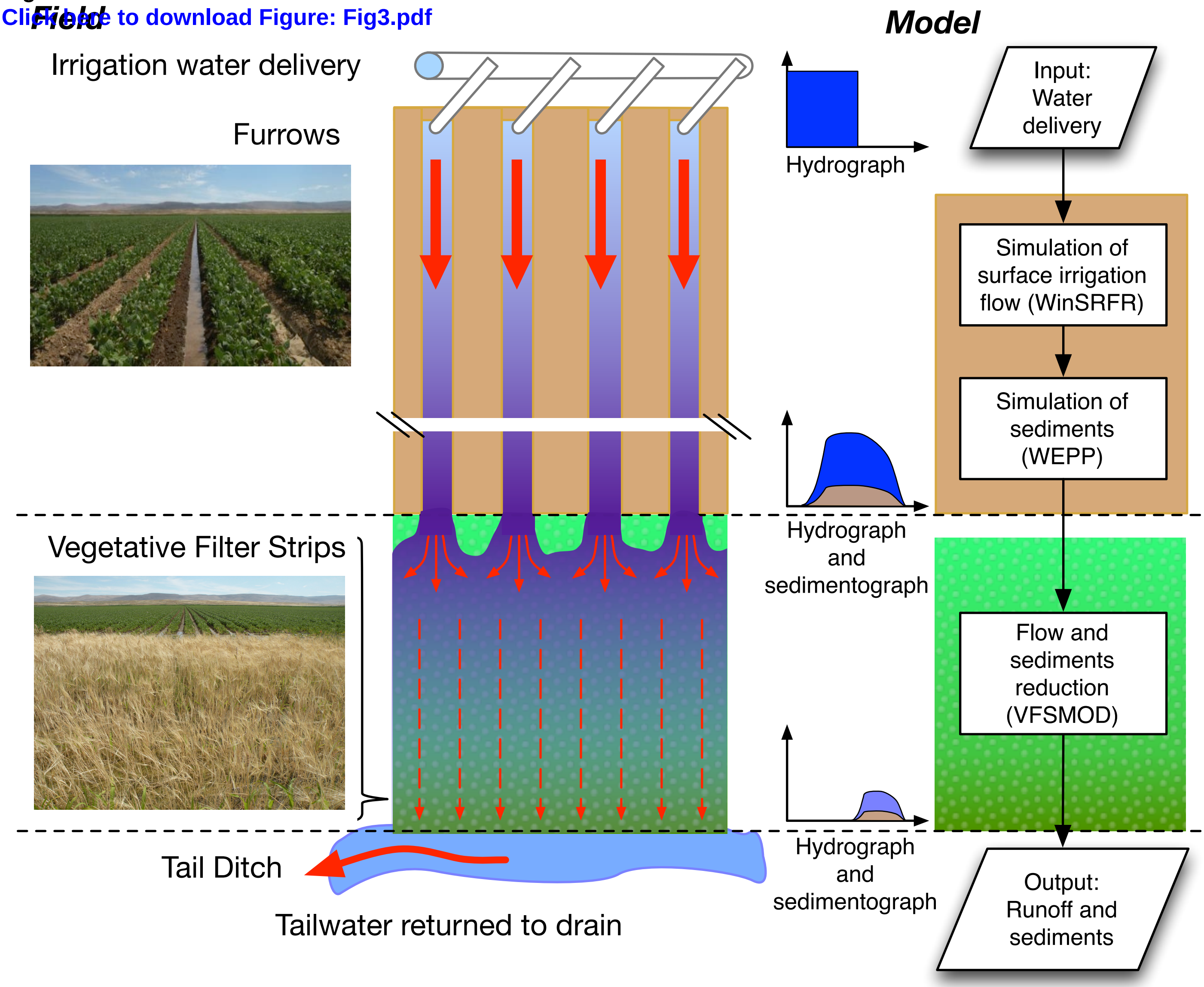

Fig 4

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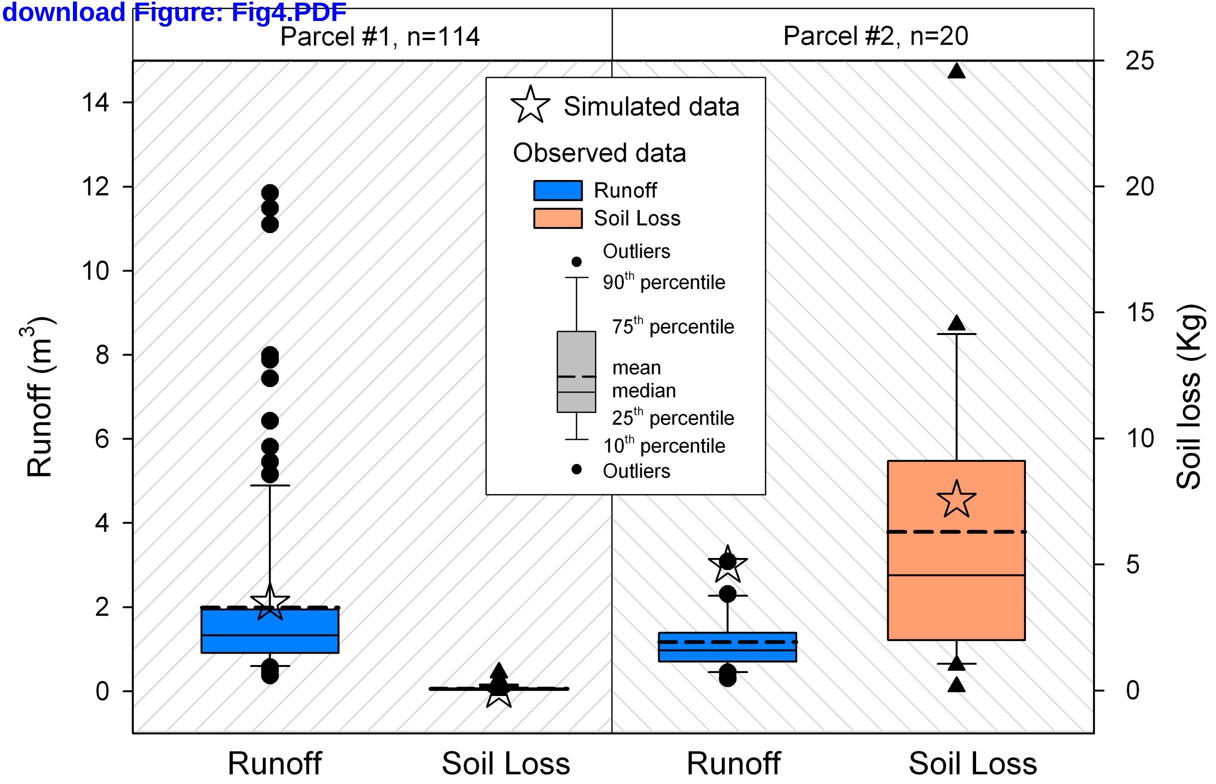

Fig 5
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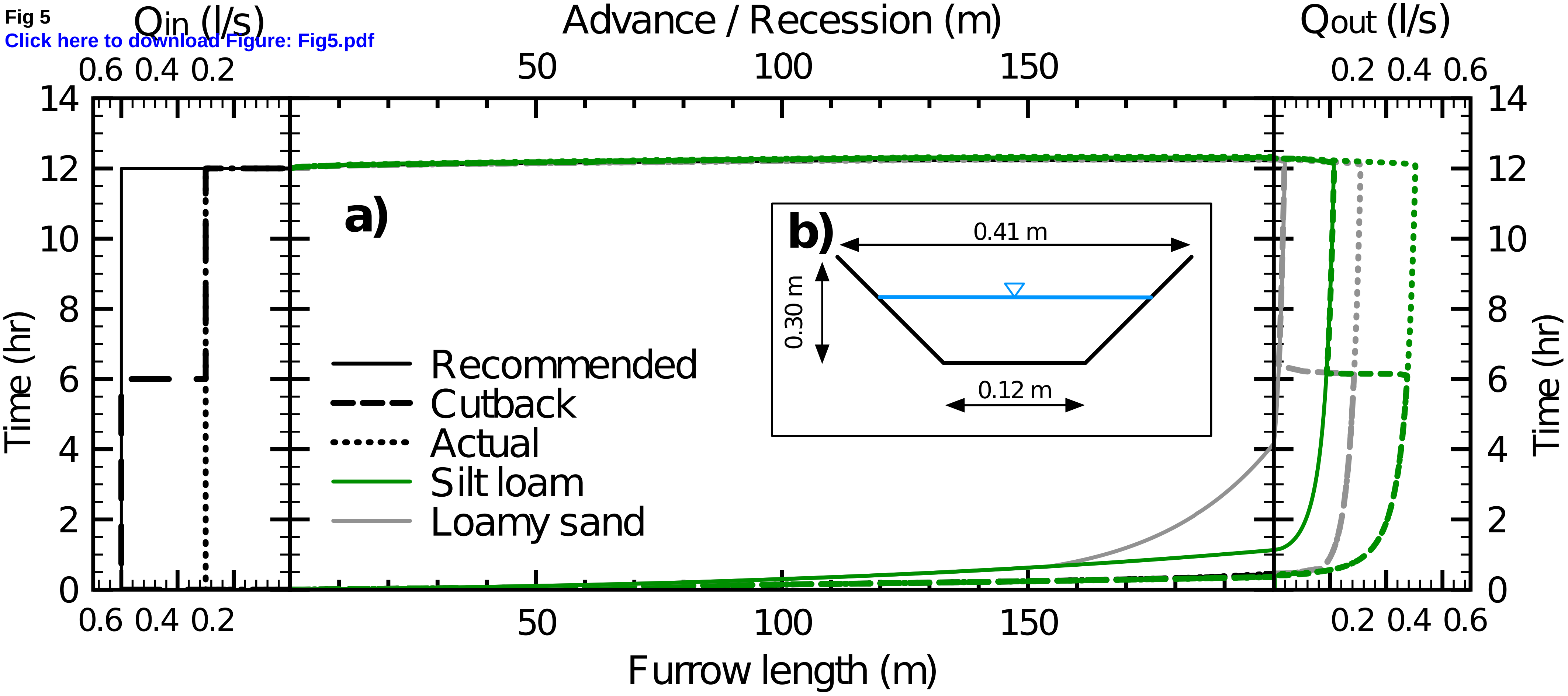

Fig 6
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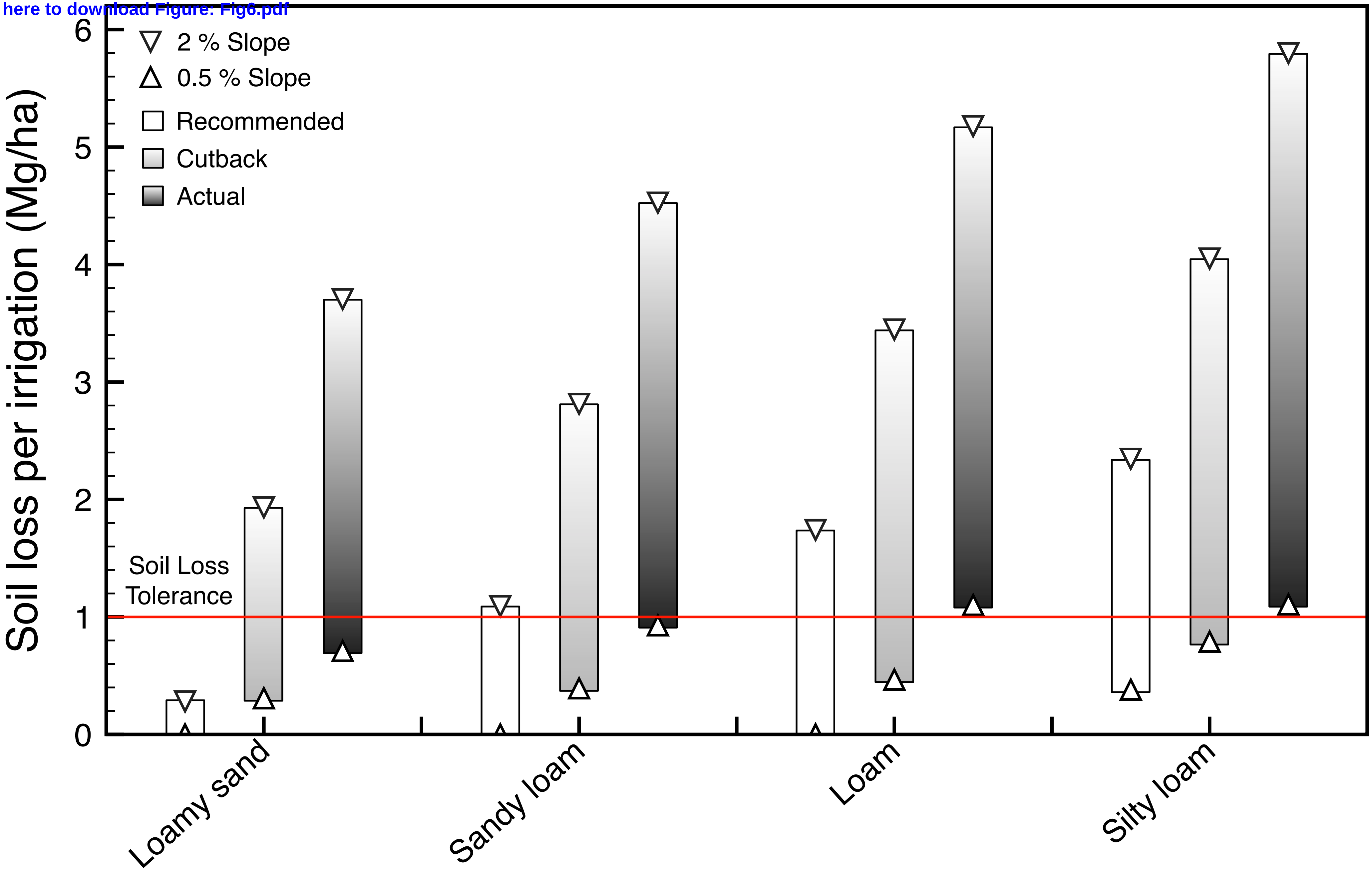

Fig 7
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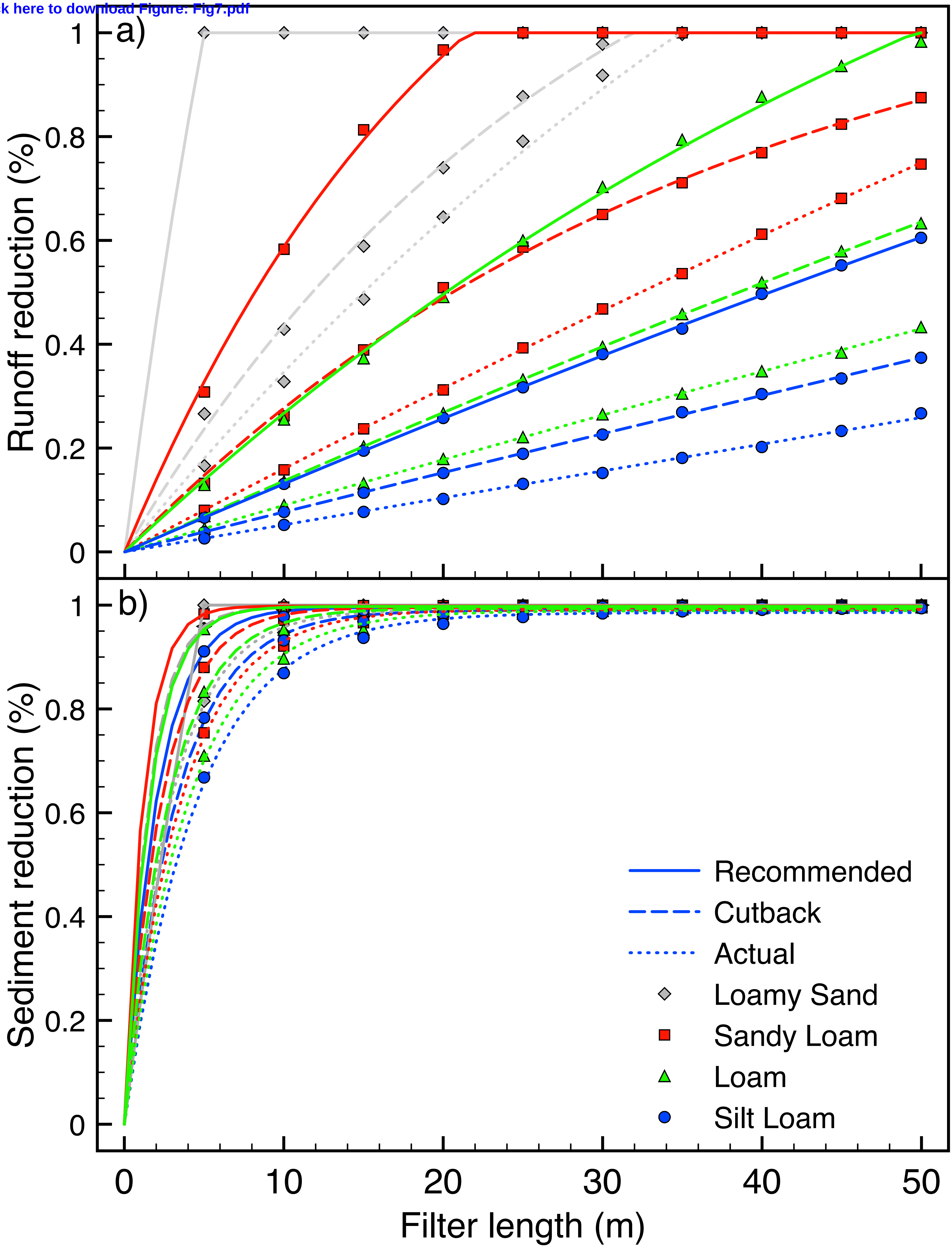

Fig 8

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