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Design and initial evaluation of a portable *in situ* runoff and sediment monitoring device

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SUMMARY

An inexpensive portable runoff and sediment monitoring device (RSMD) requiring no external electric power was developed for measuring water runoff and associated sediment loss from field plots ranging from 0.005 to 0.1 ha. The device consists of runoff gauge, sediment mixing and sectional subsampling assemblies. The runoff hydrograph is determined using a calibrated tipping bucket. The sediment mixing assembly minimizes fluid splash while mixing the runoff water/sediment mixture prior to subsampling this material. Automatic flow-proportional sampling utilizes mechanical power supplied by the tipping bucket action, with power transmitted to the sample collection assembly via the tipping bucket pivot bar. Runoff is well-mixed and subdivided twice before subsamples are collected for analysis. The resolution of this device for a 100 m^2 plot is 0.025 mm of runoff; the device is able to capture maximum flow rates up to 82 mm h^{-1} in a plot of the same dimension. Calibration results indicated the maximum error is 2.1% for estimating flow rate and less than 10% for sediment concentration in most of the flow range. The RSMD was assessed by measuring field runoff and soil loss from different tillage and slope treatments for a single natural rainfall event. Results were in close agreement with those in published literature, giving additional evidence that this device is performing acceptably well. The RSMD is uniquely adapted for a wide range of field sites, especially for those without electric power, making it a useful tool for studying soil management strategies.

1. Introduction

Soil and water degradation are among the world's most serious environmental and agricultural problems (Pimentel et al., 1995). To achieve efficient water use and conserve soil and water resources, it is crucial to better understand runoff and soil loss processes for improving conservation measures that are appropriate for different landscapes. Runoff and soil loss monitoring are required to rigorously evaluate management practices for soil and water conservation.

Depending on the specific needs and the goals at a location, various techniques and methods are available for measuring and evaluating soil and water loss. Each method has its own advantages favoring its adoption under certain conditions and limiting its use under others. Runoff plots have been used to compare soil erodibility and to assess the benefit of soil and water conservation practices (Olson and Wischmeier, 1963; Zougmoré et al., 2004). However, there are drawbacks to runoff plots, such as the monetary and time investments to establish, operate and maintain these plots. It also takes a great deal of staff time to farm and maintain the plots. Moreover, the results are easily influenced by human factors, and there is potential for large errors (Hudson, 1993). Weirs offer an accurate field estimate of runoff and facilitate sediment loss estimates in certain watersheds (Hudson, 1993; Suttles et al., 2003). However, use of weirs can neither directly assesses soil erosion hazards under different cropping and land management practices for the entire watershed, nor can it evaluate the benefit of specific land management treatments at targeted locations. Rainfall simulation can emulate natural rainfall characteristics and allow the evaluation

Abbreviations: CT, conventional tillage; NT, no-tillage; RSMD, runoff and sediment monitoring device; TRE, duration from the onset of rainfall to the end of runoff; TRI, the elapsed time from the beginning of rainfall to the start of runoff; TPR, the elapsed time from the onset of rainfall to the beginning of peak runoff.

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of relationships between rainfall amount, intensities and duration of water and soil loss. Simulators are very useful in studying the rainfall-runoff processes and mechanisms under controlled conditions. However, the major drawbacks in the use of simulators for larger plots are the cost, time and labor requirement for construction and operation, and small experimental areas do not reproduce real conditions of surface flow (Hudson, 1993).

Harmel et al. (2006) provides a good summary of alternative devices designed for monitoring and assessing runoff and soil erosion in plot and field studies. Storage tanks were originally used to measure runoff volume of small runoff plots; their use can avoid runoff partitioning and reduces the unpredictable uncertainties of the results, but the process of collecting, storing, emptying, and measuring is laborious and the sampling accuracy is inconsistent (Khan and Ong, 1997). Moreover, obtaining a representative sample is problematic, and the volume of the tank limits its use during long and/or intense rain storms (World Meteorological Organization, 1988). Multi-slot divisors are frequently used as standard devices for measuring runoff volume and soil loss from small areas (Geib, 1933; Sombatpanit et al., 1990; Sheridan et al., 1996; Franklin et al., 2001; Bonilla et al., 2006). They have the advantage of being simple to construct and operate at low-cost, and the capability of monitoring runoff and soil loss. But their use is limited to the determination of total runoff and soil loss, sediment loading, and runoff duration primarily because of the variation in the velocity distribution and non-uniformity of sediment in runoff (Laryea et al., 1997; Parker and Busch, 2013). The tipping bucket design offers an accurate measurement of runoff water for small plots (Barfield and Hirschi, 1986; Khan and Ong, 1997). Splitters are additional attachments to the tipping bucket system that provide greater flexibility for researchers to accurately estimate runoff processes, and allow for measurements of a wide variety of expected runoff rates and total volumes (Yu et al., 1997; Zhao et al., 2001). However, these devices do not completely achieve the goals of monitoring temporal variations in runoff and sediment. The Coshocton wheel sampler, a rotating slot sampler developed by Pomerene (Parsons, 1954, 1955), requires limited maintenance and no electric power and provides a single flow-proportional sample of runoff from plots or small watersheds (Edwards et al., 1976). Bonta (1999, 2002) modified the original Coshocton design for specific runoff and sediment sampling conditions. Automatic fraction samplers such as ISCO samplers (Lincoln, NE, USA), and the Runoff Measurement Instrument (Umwelt–Geräte–Technik Müncheberg, Germany, http://www.ugt-online.de) can continuously measure runoff and sediment in a specified time interval, but they have some respective impairment in monitoring runoff and soil loss. With ISCO samplers the flow rate is easily affected by the synchronism between the plug and pump cycle and incoming flow (Zhao et al., 2001). In addition, because of the limitation of a realistic maximum sample rate, non-continuous sampling may miss rapid change in sediment concentration when collecting runoff from a small area. Choosing a suitable power supply that could accommodate various flow rates is another challenge (Pinson et al., 2004). The Runoff Measurement Instrument is complex to construct and maintain, and requires auxiliary power (e.g., a alternate current or solar panel (http://ugt-online.de/en/produkte/bodenkunde/erosions-messtechnik/run-off-messeinrichtung.html). Also, its high-cost and low mobility limit its application in field scale runoff studies. There remains a distinct need to design an inexpensive portable runoff and soil loss measuring device that (1) temporally collects representative runoff samples; (2) adapts to a wide range of conditions (research plot, farmland, and natural land); (3) accurately determines the runoff hydrograph; and (4) requires no external input power to run the collector. This article describes the design, operation principle, construction details, calibration, installation and field test of such a device.

2. Materials and methods

2.1. Description of device

The portable runoff and sediment monitoring device (RSMD) was manufactured by the Northeast Institute of Geography and Agroecology, Chinese Academy of Science, Harbin, China. This device was designed for *in situ* measurement of runoff and soil loss from sloping land. Especially important is the unique adaptability of this device to remote field areas, and natural and artificial plots where no electric power is available. The portable RSMD includes three main components: (i) runoff measuring assemblies, which intercepts and directs runoff into a tipping bucket; the runoff is quantified by a tipping bucket with tips recorded via a reed switch and data logger combination; (ii) sediment mixing assembly, which minimizes fluid splash and mixes sediment in the water prior to subsampling; and (iii) sectional sampling assemblies which temporally collects samples automatically with the assembly driven by mechanical power transmitted from the tipping bucket; sampling occurs after runoff is mixed fully and subdivided twice. Details are given in Figs. 1 and 2. The cost for construction materials of each device is about $1200, with approximately 140 h of skilled labor required for fabrication and construction. The basic components of device are made of stainless steel sheet, and useful life can be more than 10 years under the maintainability. The maintenance of this device mainly involves frequently downloading the data logger to ensure data integrity, checking the operation of the tipping bucket mechanism for freedom of motion make device work well.

2.2. Runoff sampling assemblies

A PVC pipe delivers the water and sediment mixture from the plot or field area to a circular splitter having a series of equally sized V-notches (see V-notch weirs in Figs. 1, 2A and 3) for subsample division in the RSMD. This circular splitter and runoff water mixing assembly is designed such that runoff water from the PVC pipe falling onto the cone-shape base of this cylinder (see Figs. 2A and 3) is uniformly mixed. The splitter subsample is representative of the runoff mixture entering the PVC pipe. Design criteria for the sediment mixing assembly are explained below. Equal portions of the runoff volume flow through each notch in the V-notch weir. The runoff mixture from one of the V-notches is routed through a similarly designed second circular splitter with V-notches for a second sample split and the uncollected mixture is diverted to the tipping bucket.

The tipping bucket (see Figs. 1 and 2B), consisting of two symmetrical chambers divided by a vertical plate, is installed beneath the first splitter. The tipping bucket pivots on an axle positioned on the line of symmetry between the two chambers and rests in one of two stable positions (Figs. 1 and 2B). The operation principle and procedure of the tipping bucket have been described in detail by Laryea et al. (1997). The discarded runoff from the first splitter flows into one of the tipping bucket chambers; the mass in the receiving chamber increases until a critical weight is reached, which causes the tipping bucket to rotate on the axle, thereby placing the second chamber under the first splitter and discarding the water and sediment from the first chamber. This process is repeated for the duration of the runoff event. A reed switch is placed on the collector frame so that for each tipping bucket tip, a pulse signal from the reed switch is recorded concurrently with the time of each tip on a battery powered data logger. The number of tips is stored in the data logger each minute. Based on the calibration of the mean tip volume for different flow rates, the number of tips per minute is converted to runoff volume. In the present