Studies of Scale and Processes in Hydrologic Modeling on the Lucky Hills Watershed

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Abstract

Hydrologic and sediment yield data collected from Lucky Hills 104 within the Walnut Gulch Experimental Watershed have been used extensively to study the effects of scale in the KINEROS model. These studies show that lumping of parameters derived at the small scale into increasingly less complex geometry has the effect of reducing runoff volume, peak and sediment yield. Model simulations mirror observations at the Lucky Hills watersheds showing a decrease in runoff per unit area as watershed size increases. Studies of rainfall variability on model response show that even at <5 ha scale, data from a single gauge cannot adequately describe rainfall input, and can lead to errors in runoff modeling. Studies of watershed representation indicate that runoff volume can be simulated using less complex geometries if equilibrium storage of runoff is maintained. Likewise sediment yield can be simulated using a simplified watershed representation by increasing the entrainment of sediment by raindrop impact on hillslopes even as entrainment by flowing water decreases as fewer channels are represented in the model.

Keywords: hydrologic modeling, semiarid rangeland watersheds, erosion, precipitation, spatial variability

Introduction

In order to develop, calibrate and validate watershed hydrology models, hydrologic data collected at instrumented watersheds are required. This paper presents an overview of data collection at the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) Lucky Hills 104 watershed (Renard et al. 1986), and describes how these data have been used with the KINEROS2 model (Smith et al. 1995) to simulate hydrologic processes on small semiarid watersheds.

Lucky Hills Intensive Study Sites

In 1961, researchers identified two watersheds draining into stock ponds that were thought to be indicative of typical environments on the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, AZ. One of these, Kendall's pond 20, drained a 128 acre (52 ha) stable grassland watershed. The other, Lucky Hills pond 23, drained a 115 acre (46.7 ha) shrub-dominated, creosote bush and acacia watershed.

In 1961 and 1962, rainfall and runoff monitoring was initiated at these two stock pond watersheds, but data were of limited value in developing rainfall-runoff relationships. "Percentages of the rainfall that appeared as runoff in each of these ponds were so variable, however, that no comparison of the two areas could be made. Owing, probably, to unresolved characteristics of the drainage areas, storms of similar amounts and intensities on the same area produced differing amounts of runoff (Kincaid et al. 1964)."

Therefore, the researchers identified two smaller 'unit-source' watersheds at the upper end of the stock pond watersheds. "A 'unit-source' watershed is defined as a natural drainage area that has relatively homogenous soil and vegetation cover, that is subject to essentially uniform precipitation, and for which any geologic influences on the surface outflow are areally representative (Kincaid et al. 1966)." Two small upland areas were selected for more intensive study. In 1962 the first runoff was measured at Kendall Watershed 112 (4.6 acres, 1.9 ha) and Lucky

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Hills Watershed 101 (3.2 acres, 1.3 ha). In each of these small watersheds, runoff measuring weirs, rain gauges and soil moisture blocks were installed.

The location of Lucky Hills lent itself to paired watershed study, because an adjacent watershed had similar soil and vegetation characteristics. By 1963, a nested watershed had been instrumented at Lucky Hills Watershed 103 (9.1 acres, 3.7 ha.) which contained the Lucky Hills 101 watershed, and drained into the stock pond. A second nested watershed was instrumented at Lucky Hills 104 (11.2 acres, 4.5ha). While Lucky Hills 104 did not drain into a stock pond, the drainage network lent itself to establishing nested subcatchments on the northeast (Lucky Hills 106, 0.85 acres, 0.36 ha) and northwest (Lucky Hills 102, 3.6 acres, 1.46 ha) forks (Figure 1). The Lucky Hills watershed complex was fenced, and there has been no grazing by domestic livestock on this land since 1963 (Osborn and Simanton 1983), though rabbits and other small herbivores may graze on the watershed. Soils on the watershed are mapped as Luckyhills-McNeal Sandy Loam (Ustochreptic Calciorthid) (Breckenfeld et al. 1995).

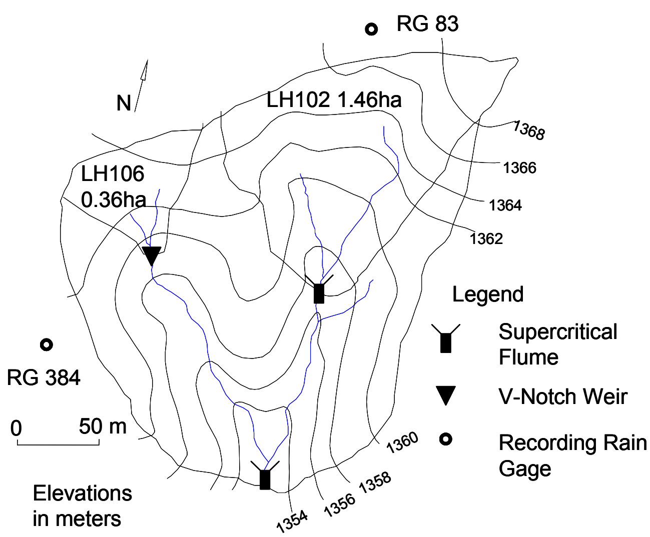

Figure 1. The Lucky Hills 104 showing the locations of the two nested watersheds, and location of current rain gauges and flumes.

Data Collection at Lucky Hills 104

Rainfall and runoff data have been collected at Lucky Hills 104 watersheds since 1963 when Rain gauge 83 and V-notch weirs 104 (LH104) and 102 (LH102) were installed. Rain gauge 384 was added in 1964, and a weir was installed on Lucky Hills 106 (LH106) in 1965.

In 1978 the wier at LH104 was replaced with a supercritical flume and traversing slot sampler (Renard et al. 1986). In 1977 a concrete flume replaced the weir at LH102. This concrete flume was subsequently replaced with a supercritical flume and traversings slot sampler in 1998. Since the instrumentation was installed in the early 1960s, rainfall and runoff data have been collected with only short interuptions for upgrading equipment, which generally occurred during the winter. However, there have also been periods of more intensive sampling, such as during Monsoon ’90 (Kustas and Goodrich 1994), when a dense rain gauge and soil moisture monitoring network were installed. Soil moisture changes with depth were also monitored at six locations under shrub and bare conditions (Canfield and Lopes 2000, Hymer et al. 2000).

Sediment data are more difficult to collect and prone to sampling errors, so sediment data are not available for many events for which rainfall and runoff data are available. Intially, coarse particle load was measured after each event by removing and weighing the sediment in approach boxes behind the wiers. Integrated depth pump samplers were added in 1973 to collect suspended sediment samples. The traversing slot sampler, added to LH104 in 1978 and to LH102 in 1998, was developed to collect depth integrated samples for use in computing total load discharge through an event. The use of different sampling equipment has allowed reasearchers to asses the viability of different sampling methods using data from the Lucky Hills (Simanton et al. 1993)

There have been several efforts to characterize the topography of the watershed. A five-foot contour map, from field survey, was used in the first papers describing research at the watershed (e.g. Osborn and Lane 1969). A topographic map was prepared from a 1975 areal survey which resulted in a 1’ contour map of the watershed (e.g. Faures et al. 1995), which was the basis for watershed characterization in many of the studies of watershed complexity and model response. A 2.5 m x 2.5 m DEM was prepared based on field survey, and used to relate to soil variability to topographic characteristics (Canfield 1998). The relationships between topographic characteristics and soil characteristics could then be used to parameterize the spatial variability of infiltration and soil erosion parameters (Canfield and Goodrich 2000, Canfield et al. 2001).

Plot scale studies have been conducted to determine the hydrologic impact of reduction of canopy cover and the increase of grass cover (Kincaid and Williams 1966, Schreiber and Kincaid 1967), a desirable outcome for management of rangelands. There was also a largely failed attempt to convert all of Lucky Hills 106 (0.36 ha) and Lucky Hills 102 (1.46 ha) from brush to grass (Woolhiser et al. 1990) using herbicides and physical treatments.

Hydrologic Process Studies and Model Development

Analysis of runoff data collected during the first two years of operation, 1963 and 1964, showed that anywhere from 50% to 150% more runoff was generated per unit area on 6’x12’ plots than from the small watersheds (Kincaid et al. 1966). Researchers recognized that some of this difference could be attributed to watershed characteristics, and some could be attributed to spatial variability of precipitation. Therefore, early analyses of watershed data showed that even at the ‘unit-source’ scale, watershed chacteristics and spatial variability of precipitation affect hydrologic response.

Because of the length of record, and the density of the rainfall and runoff data, the Lucky Hills 104 data has become important for studying hydrologic process in the semiarid desert southwest. Early on, researchers were able to develop regression relationships to relate rainfall to runoff on the small watersheds at the Lucky Hills (Osborn and Lane 1969). Data from Lucky Hills have been used to validate USLE (Renard et al. 1974), as well as a distributed version of RUSLE using data in a GIS (Yitayew et al. 1999). In addition, the availability of these detailed data have made it possible to validate discriptive hydrologic models that describe the temporal and spatial variability of rainfall, runoff and sediment yield on semiarid watersheds. Specifically, the KINEROS2 model (Smith et al. 1995) has been used to describe, model and better understand hydrologic processes on the Lucky Hills 104 watershed.

The KINEROS2 Model

The KINEROS2 model is a distributed runoff-erosion model based on Hortonian overland flow theory, and, therefore, well-suited to describing the hydrodynamics of runoff and erosion on semiarid watersheds, where infiltration rates are low, and rainfall is infrequent but intense. The model allows for spatial variable rainfall input, channel transmission losses, and spatial variability of watershed characteristics such as soils, slopes and vegetation.

KINEROS2 is particularly well suited for modeling rangeland environments, because it can be parameterized to describe the variability of infiltration on hillslopes, which is best described as a distribution of values (e.g. Paige et al. 2002). The developers of KINEROS2 recognized that the distribution of infiltration can be described according to a mean and coefficient of variation (Woolhiser and Goodrich 1988). This distribution of infiltration more realistically describes the partial area response seen on semiarid rangeland watersheds such as Lucky Hills.

Runoff is treated in KINEROS2 with a one-dimensional continuity equation applicable to both overland and channel flow. Sediment entrainment and transport on hillslopes and channels is treated as an unsteady, one-dimensional convective transport phenomenon, using a continuity equation similar to that for runoff. Sediment flux on a hillslope has two independent sources, raindrop-induced entrainment and flow-induced entrainment. Watershed geometry is represented in KINEROS2 as a combination of overland flow plane and channel elements, with plane elements contributing lateral flow to the channels or to the upper end of first order channels (Figure 2).

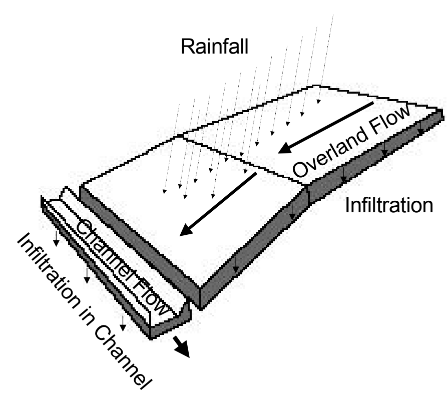

Figure 2. A schematic representation of the geometric representation of hillslopes and channels in the KINEROS2 model as well as the runoff processes simulated in the model.

Each plane may be described by its unique parameters, initial conditions and precipitation inputs. Each channel element may be described by its unique parameters as well. By allowing parameters and rainfall to vary spatially, KINEROS2 can take advantage of the wealth of spatial and temporal data from Lucky Hills to better describe and understand the effects of rainfall and watershed characteristics on runoff and sediment yield.

Results of Modeling Studies

The KINEROS2 model has been used to study the effect of rainfall spatial variability on runoff; the effect of soil moisture on runoff; the effect of geometric complexity on model response for runoff and erosion; and the effect of changes in vegetative cover on runoff.

Measuring rainfall and modeling runoff

Researchers recognized early that multiple rain gauges were necessary in order to capture the spatial distribution of rainfall (Kincaid et al. 1966). As such, there have always been at least three recording rain gauges to measure precipitation at the Lucky Hills 103 and 104 watersheds. While monsoon rainfall had been known to be highly spatially variable, the experiments performed during Monsoon '90 experiment (Kustas and Goodrich 1994) allowed hydrologists to better understand the spatial variability of monsoon rainfall at scales less than 5 ha, and its effect on infiltration and runoff. A monitoring network was devised to better sample the spatial variability of rainfall on Lucky Hills 104 using a series of non-recording and recording rain gauges (Goodrich et al. 1995). Forty-eight of the non-recording gauges were located on a 30 m grid across the watershed. Nine recording rain gauges with collocated non-recording gauges were located in areas of homogenous slope and orientation. Three vectopluviometers were employed to determine the orientation of rainfall. Analysis of these data using statistical and geostatistical methods indicated that:

- Total error for point rainfall measured from a non-recording gauge is 4-5% for storms greater than 15 mm, and greater than this for storms smaller than 15 mm.
- There were gradients in total rainfall depth which represented 4-14% error over 100 m. Therefore, a single gauge is inadequate for monitoring total rainfall depth, even on a watershed as small as Lucky Hills 104.
- The rainfall intensity variation did not change greatly across the catchment, so a single recording rain gauge is adequate for capturing temporal variability at the < 5 ha scale.

A follow-up study to the rainfall monitoring determined the relative impact of changes in rainfall on runoff modeling using the KINEROS model (Faures et al. 1995). This study found that:

- Assuming rainfall is uniformly distributed in space can lead to large errors in modeled runoff peak and volume.
- Using a single recording rain gauge and four well-distributed non-recording gauges, the sampling resolution approached the resolution of the 60-gauge dense rain gauge network, and model-estimated peak and volume were within 10% of the dense network values.

These two studies indicate that non-recording rain gauges can sample the spatial variability of rainfall at the < 5 ha scale, and that a single recording gauge can capture the temporal variability adequately for model estimates.

Soil moisture monitoring data collected in Monsoon '90 showed that soil moisture is spatially and temporally variable on the watershed (Whitaker 1993). A sensitivity analysis of soil moisture measurement methods showed that runoff estimates from KINEROS on the Lucky Hills are relatively insensitive to different methods of soil moisture estimation (Goodrich et al. 1994). This implies that model predictions will not likely be improved by improving the soil moisture estimate.

Watershed representation and its effect on runoff and erosion modeling

Because so much spatial data are available for the Lucky Hills, the data set lends itself to the study of spatial complexity and model response. Early researchers attributed the reduced runoff per unit area noted at the watershed, in part, to the impact of channels and depression storage (Kincaid et al. 1966). In model terms, the reduced runoff per unit area will depend both on the model parameters and the complexity of the channel network used in the model. KINEROS2 simulations at Lucky Hills 104 showed that runoff peak and volume decrease systematically as the watershed is represented with increasingly fewer channels (Lopes and Canfield (in press)). Goodrich et al. (1997) were able to show that equilibrium storage of runoff on a watershed can be maintained as the watershed is represented with increasingly fewer channels. These researchers assumed an impermeable surface, and showed how roughness could be increased as subcatchments were represented as a single overland flow plane. Using this method, he was able to show that runoff volume could be predicted without significant degradation (Nash-Suttcliffe statistic >0.9), from a complex representation with 263 elements draining hillslopes of a few hundred square meters, to a representation of 17 elements draining hillslopes of larger than 5000 square meters.

In contrast, as fewer channels are represented in KINEROS2, sediment yield is largely a function of event characteristics. For events with approximately a 2 year return period sediment yield was approximately the same for watershed representations with from a 312 element model draining hillslopes of about 200 square meters to an 18 element model draining hillslopes greater than 5,000 square meters (Lopes and Canfield, (in press)). However, runoff decreased systematically with less complex model representations for these events. In contrast, for events of longer than two-year return periods, sediment yield is affected by watershed representation with less complex representations underpredicting sediment yield, presumably because channels are a more important source of sediment for large events. Studies of model representations of erosion in the KINEROS2 model on the Lucky Hills 104 have shown that as the model representation becomes more simplified, sediment entrainment can be maintained by increasing the contribution from splash erosion at the expense of entrainment by flowing water (Canfield et al 2002). However, model predictions become less accurate for less complex model representations.

Conclusions

While scale effects and spatial variability in hydrology are widely recognized as problems that need to be addressed, there are limited data sets for studying these problems. Studies from the USDA-ARS Lucky Hills 104 Watershed at Walnut Gulch have been used to better understand the spatial variability of rainfall, the spatial variability of soil moisture, partial area response, and spatial variability of soils and infiltration characteristics. By using the data from the Lucky Hills 104 to parameterize the KINEROS2 model, researchers have been able to better understand these hydrologic processes and the effects that sampling may have on model predictions.

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References

Breckenfeld, D.J., W.A. Svetlik, and C.E. McGuire. 1995. Soil survey of Walnut Gulch Experimental Watershed. U.S. Department of Agriculture, Soil Conservation Service.

Canfield, H.E. 1998. Use of Geomorphic Indicators in Parameterizing an Event-based Sediment-yield Model, Ph.D. Dissertation, Agricultural and Biosystems Engineering, University of Arizona, Tucson, AZ.

Canfield, H.E., and D.C. Goodrich. 2000. Estimating the spatial variability of saturated hydraulic conductivity on a small semiarid rangeland watershed using geostatistical techniques. Supplement to EOS Transactions, AGU Fall Meeting 81:48.

Canfield, H.E., and V.L. Lopes. 2000. Simulating soil moisture change in a semiarid rangeland watershed with a process-based water-balance model. In P. Ffolliott, ed., Proceedings of the Conference on Land Stewardship in the 21st Century: The Contributions of Watershed Management, Tucson, AZ, March 13-16, 2000, pp. 316-319. U.S. Forest Service, Rocky Mountain Research Station, Ft. Collins, CO RMRS P-13.

Canfield H.E., V.L. Lopes, and D.C. Goodrich. 2001. Hillslope characteristics and particle size composition of surficial armoring on a semiarid watershed in the southwestern U.S. Catena 44:1-11.

Canfield, H.E., V.L. Lopes, and D.C. Goodrich. 2002. Catchment geometric representation and identification of sediment yield parameters in a distributed catchment model. In D. Frevert and G. Leavesley, eds., Proceedings of the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, July 28-August 1, 2002, Session 8B, pp. 1-12 (CD-ROM).

Faures, J.M., D.C. Goodrich, D.A Woolhiser, and S. Sorooshian. 1995. Impact of small-scale spatial rainfall variability on runoff modeling. Journal of Hydrology 173:309-326.

Goodrich, D.C., T.J. Schmugge, T.J. Jackson, C.L. Unkrich, T.O. Keefer, R. Parry, L.B. Bach, and S.A. Amer. 1994. Runoff simulation sensitivity to remotely sensed initial soil water content. Water Resources Research 30:1393-1405.

Goodrich, D.C., J.M. Faures, D.A. Woolhiser, L.J. Lane, and S. Sorooshian. 1995. Measurement and analysis of small-scale convective storm rainfall variability. Journal of Hydrology 173:283-308.

Goodrich, D.C., L.J. Lane, R.A. Shillito, S.N. Miller, K.H. Syed, and D.A. Woolhiser. 1997. Linearity of basin response as a function of scale in a semi-arid watershed. Water Resources Research 33:2951-2965.

Hymer, D.C., M.S. Moran, and T.O. Keefer. 2000. Soil water evaluation using a hydrologic model and calibrated sensor network. Soil Science Society of America Journal 64:319-326.

Kincaid, D.R., J.L. Gardner, and H.A. Schreiber. 1964. Soil and vegetation parameters affecting infiltration under semiarid conditions. IASH Publication 65:440-453.

Kincaid, D.R., H.B. Osborn, and J.L. Gardner. 1966. Use of unit-source watersheds for hydrologic investigations in the semiarid southwest. Water Resources Research 2:381-392.

Kincaid, D.R., and G. Williams. 1966. Rainfall effects on soil surface characteristics following range improvement treatments. Journal of Range Management 19:346-351.

Kustas, W.P., and D.C. Goodrich. 1994. Preface. Water Resources Research 30:1211-1225.

Lopes, V.L., and H.E. Canfield. 2003. Effects of watershed representation on runoff and sediment-yield modeling. Journal of the American Water Resources Association (in press).

Osborn, H.B., and L. Lane. 1969. Precipitation-runoff relations for very small semiarid rangeland watersheds. Water Resources Research 5:419-425.

Osborn, H.B., and J.R. Simanton. 1989. Gullies and sediment yield. Rangelands 11:51-56.

Osborn, H.B. and J.R. Simanton. 1983. Runoff estimates for thunderstorm rainfall on small rangeland watersheds. Hydrology and Water Resources in Arizona and the Southwest 13:9-15.

Paige, G.B., J.J. Stone, D.P. Guertin, and L.J. Lane. 2002. A strip model approach to parameterize a coupled Green-Ampt kinematic wave model. Journal of the American Water Resources Association 38:1363-1377.

Renard, K.G., J.R. Simanton, and C.E. Fancher. 1986. Small watershed automatic water quality sampler. In Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, NV March 24-27, 1986, pp. 1:51-58.

Renard, K.G., J.R. Simanton, and H.B. Osborn. 1974. Applicability of the universal soil loss equation to semiarid rangeland conditions in the southwest. Hydrology and Water Resources in Arizona and the Southwest 4:18-31.

Schreiber, H.A., and D.R. Kincaid. 1967. Regression models for predicting on-site runoff from short-duration convective storms. Water Resources Research 3:389-395.

Simanton, J.R., W.R. Osterkamp, and K.G. Renard. 1993. Sediment yield in a semiarid basin: Sampling equipment impacts. In Yokohoma Symposium on Sediment Problems: Strategies for Monitoring, Prediction and Control, July 1993. IAHS Publishers.

Smith, R.E., D.C. Goodrich, D.A. Woolhiser, and C.L. Unkrich. 1995. KINEROS - A Kinematic Runoff and Erosion Model. In V.J. Singh, ed., Computer Models of Watershed Hydrology, pp. 697-632.Water Resources Publications.

Whitaker, M.P.L., 1993. Small-scale spatial variability of soil moisture and hydraulic conductivity in a semi-arid rangeland soil in Arizona. Unpublished M.S. Thesis, University of Arizona.

Woolhiser, D.A., and D.C. Goodrich. 1988. Effects of storm rainfall intensity patterns on surface runoff. Journal of Hydrology 102:335-354.

Woolhiser, D.A., D.C. Goodrich, W.E. Emmerich, and T.O. Keefer. 1990. Hydrologic effects of brush to grass conversion. In Watershed Planning and Analysis in Action Symposium Proceedings of IR Conference, Durango, CO, July 9-11, 1990. Watershed Management, IR Division, American Society of Civil Engineers.

Yitayew, M., S.J. Pokryzwka, and K.G. Renard. 1999. Using GIS for facilitating erosion estimation. Applied Engineering in Agriculture 15:295-301.