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Modelling scale-dependent runoff generation in a small semi-arid watershed accounting for rainfall intensity and water depth

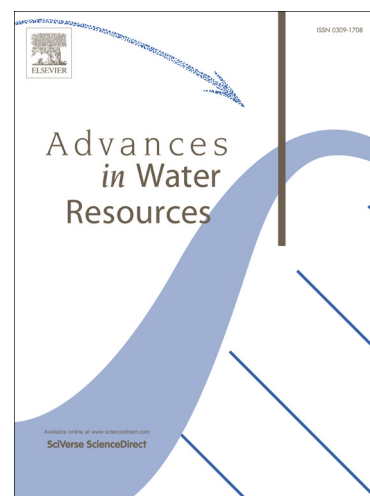Christoph Langhans, Gerard Govers, Jan Diels, Jeffry J. Stone, Mark A. Nearing

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1 Title: Modelling scale-dependent runoff generation in a small semi-arid

2 watershed accounting for rainfall intensity and water depth

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16

Abstract:

Observed scale effects of runoff on hillslopes and small watersheds derive from complex interactions of time-varying rainfall rates with runoff, infiltration and macro- and microtopographic structures. A little studied aspect of scale effects is the concept of water depth-dependent infiltration. For semi-arid rangeland it has been demonstrated that mounds underneath shrubs have a high infiltrability and lower lying compacted or stony inter-shrub areas have a lower infiltrability. It is hypothesized that runoff accumulation further downslope leads to increased water depth, inundating high infiltrability areas, which increases the area-averaged infiltration rate. A model was developed that combines the concepts of water depth-dependent infiltration, partial contributing area under variable rainfall intensity, and the Green-Ampt theory for point-scale infiltration. The model was applied to rainfall simulation data and natural rainfall – runoff data from a small sub-watershed (0.4 ha) of the Walnut Gulch Experimental Watershed in the semi-arid US Southwest. Its performance to reproduce observed hydrographs was compared to that of a conventional Green-Ampt model assuming complete inundation sheet flow, with runon infiltration, which is infiltration of runoff onto pervious downstream areas. Parameters were derived from rainfall simulations and from watershed-scale calibration directly from the rainfall – runoff events. The performance of the water depth-dependent model was better than that of the conventional model on the scale of a rainfall simulator plot, but on the scale of a small watershed the performance of both model types was similar. We believe that the proposed model contributes to a less scale-dependent way of modelling runoff and erosion on the hillslope-scale.

2

1 Introduction

The scale-dependency of runoff and infiltration has been recognized widely. In studies that compare runoff at different scales of a hillslope, scale effects appear as reduced runoff coefficients with increasing scale [1-7]. Models that try to reduce scale-dependency in the calculation of runoff generation have concentrated on various effects. Among the explanations for scale effects, variability and duration of a rainstorm are probably the most uncontroversial ones: even on a perfectly homogeneous surface runoff coefficients can be expected to decrease with slope length (or area) due to the infiltration of runoff water in pervious downstream areas (runon infiltration) during periods of low rainfall intensity and/or after the rainfall event. Stomph et al. [8] have quantified the effect of storm duration and slope length on artificial slopes in the laboratory, finding that shorter rainfall durations and longer slopes produce the largest scale effects. Wainwright and Parsons [9] simulated runoff coefficients with a simple storage model, allowing runon infiltration, which is defined as infiltration of water produced by rainfall excess further upslope [10]. They found that the average rainfall intensity and variability of rainfall strongly influenced runoff coefficients, while the reduction in runoff coefficients with slope length of the simulated hillslope was dependent on slope gradient and the hydraulic roughness coefficient. The effect of spatial variation in infiltration capacity on scale effects is more controversial than the temporal effect. Modelling studies have created randomly distributed hydraulic variables, very often saturated hydraulic conductivities (K_s), with or without spatial correlation, and have computed the sensitivity of runoff production to the coefficient of variance and/or the spatial structure of the variance [10-12]. If runon infiltration is allowed, which means that runoff produced upstream infiltrates if it flows over unsaturated areas, substantial scale effects appear [13-15].

3

64 It has been suggested that heterogeneity in the context of runon infiltration increases scale

65 effects, because the likelihood that runoff flows onto areas of very high infiltration capacity is

66 increased with increasing scale, thereby reducing runoff connectivity [7, 16]. However, the

67 effect is dependent on rainfall intensity and duration, the pattern of runoff concentration and

68 typical scale of heterogeneities [17], and it has not been quantified yet.

69   Runon infiltration is usually modelled as sheet flow entering unsaturated modelling units

70 (cells or pixels), supplying water for infiltration in the same way as rainfall on the whole

71 surface of the modelling unit [e.g. 13]. In such a conceptualization a constant hydraulic

72 conductivity for the whole modelling unit is assumed. Runon infiltration has also been

73 modelled to increase with inundation of a microtopography, albeit without a systematic

74 variation of hydraulic conductivity within the microtopography [10]. However, in

75 environments with a clear microtopographical pattern, the local distribution of hydraulic

76 conductivities is not completely random nor constant, but dependent on the relative elevation

77 within the microtopography. Lyford and Qashu [18] found hydraulic conductivities to be 2.6

78 times higher under creosote bushes (*Larrea tridentata*) and Palo Verde (*Cercidium*

79 *microphyllum*), compared to the lower lying inter-shrub area. Similarly, Johnson and Gordon

80 [19] have found 2 – 2.5 times higher infiltration rates under sagebrush (*Artemisia tridentata*)

81 as compared to the inter-shrub areas. For the Mediterranean semi-arid rangeland

82 environments it has been described how increased infiltration rates occur closer to plants as a

83 consequence of mound build-up and improvement of the physical and chemical soil properties

84 around the plant [e.g. 20, 21]. Dunne et al. [22] have proposed a model for steady state

85 infiltration that accounts for these systematic patterns. In their model infiltration per unit area

86 increased with increasing runoff water depth towards the foot of a slope. This increase is

87 achieved by inundation of parts of an elevation-dependent distribution of hydraulic

88 conductivities, where higher conductivities are associated with higher elevation of the

89　microtopography. The typical distance between mounded plants may influence runoff

90　thresholds and scale effects [23]. Dunne et al. [22] combined the concept of water depth-

91　dependent infiltration with the concept of partial contributing area for runoff production in

92　order to explain the convex shape of shrub-covered hillslopes in Kenya. However, they did

93　not account for temporal variations in rainfall intensity and/or infiltration capacity. Also in

94　agricultural environments the spatial variation in infiltration capacity shows clear structure,

95　leading to water depth dependent infiltration rates. Bresson and Valentin [24] showed that on

96　tilled fields a sedimentary crust with a low hydraulic conductivity builds up in the micro-

97　valleys while the micro-slopes and ridges are covered by a structural crust with much higher

98　conductivity. Fox et al. [25] have subsequently shown in a laboratory study that this

99　phenomenon can lead to a fourfold increase in average hydraulic conductivity with increasing

100　water depth. Langhans et al. [26-28] have shown that under varying inflow and rainfall

101　intensity rates on small rainfall simulation plots infiltration rates increase as inflow, rainfall

102　intensity, water depth and inundated area increase. They have accounted for these effects in a

103　water-depth dependent infiltration model based on Green-Ampt [27]. Clearly, if runon

104　infiltration is water depth-dependent this may produce scale effects as, generally, water depths

105　can be expected to increase with increasing contributing area. While both temporal variation

106　in rainfall (and infiltration) and the depth-dependency of infiltration may cause scale effects, a

107　modelling framework integrating both effects has not yet been empirically tested on both the

108　rainfall simulation plot-scale and the hillslope or small catchment-scale under natural rainfall

109　conditions.

110　　The model first described in Langhans et al. [27] for a steady state case, integrates

111　temporal, water depth and rainfall intensity effects and enables the exploration of the relative

112　importance of these effects on scale effects. In the present study, behaviour and performance

113　are compared to a similar baseline model without water depth-dependency and with a sheet

5

114 flow assumption. Data for testing the models were rainfall simulations on plots, and small

115 catchment runoff measurements, constituting two typical scales where we would expect

116 runoff generation rates to decrease from plot- to catchments-scale. We chose to form

117 infiltration expressions with parameters that are effective at the local scale (resolution) of

118 approximately 1 m² [29]. The actual resolution of a model unit in a distributed model should

119 be similar to the typical scale length of microtopography to be able to capture the full process

120 of interaction between runoff and microtopography. The typical scale length therefore

121 depends on land use: in agricultural systems, tillage implements determine the width of the

122 microtopography (~0.3 m), while in semi-arid rangeland of the study area shrubs on mounds

123 are organized in intervals of ~1.5 m. An advantage of conceptualizing processes at the local

124 scale is that effective parameters can be readily found by parameterizing the model with

125 rainfall simulation data, because the scale of modelling units and experimental plots are

126 similar and it can be assumed that processes within the experimental plot resemble those of

127 the modelling unit.

128 In this study we seek to answer the following questions: (1) can we observe scale effects

129 in a data set of rainfall simulations and runoff data from small catchments? (2) Can both

130 watershed-scale infiltration models be successfully calibrated using rainfall simulation data or

131 is calibration from watershed-scale runoff data necessary? (3) Does the incorporation of the

132 water depth-dependency and runon infiltration into a Green-Ampt based model improve

133 performance?

134

6

2 Methods

This section describes the site and the rainfall simulation data that were used to parameterize the baseline model and the new model to be tested. Further, this section describes the natural rainfall data that were used to validate the models' results when parameterized with rainfall simulation data and to obtain model parameters by calibration and validation against runoff hydrographs. The parameterization is described in detail in section 3.4.

2.1 Site description

The Walnut Gulch Experimental Watershed (WGEW) of the United States Department of Agriculture (USDA) is a semi-arid watershed located in Southeast Arizona, southwest United States in the transition zone between the Sonoran and Chihuahua desert (Figure 1). Runoff occurs mainly in the summer months during and shortly after major convective storms. Storms of lower intensity during winter months rarely produce runoff. Within the WGEW, the Lucky Hills Site is a 0.4 ha sub-watershed (LH- 106) with an average slope of 7.6 %, and equipped with an H-flume [30]. Figure 2 is a contour map of the watershed, under-laid with a panchromatic satellite image from 7 July 2010 (Quickbird, 0.6 m resolution). The darker gray areas represent single shrubs or agglomerations of a few shrubs (1 to 2 m in diameter), within a network of gravely soil or scattered forbs and grasses, mostly with a stony upper soil layer (light grey areas). The soil is classified as very gravely sandy loam without a topsoil [31]. Dominant shrubs species within the watershed include Creosote (*Larrea tridentata*) and Whitethorn (*Acacia constricta*) on mounds of looser, mulched soil with fewer stones (Figure 3).

[location of Figure 1, 2 and 3]

7

158

2.2 Rainfall simulations and runoff measurements

160   Rainfall simulations with rainfall intensities between 25 and 216 mm h^{-1} were conducted

161 between 2004 and 2008 during summer months about 100 meters south of the outlet of LH-

162 106. Rainfall simulations were conducted with a central oscillating boom rainfall simulator

163 with four nozzles (Veejet 80100) attached at 1.52 m intervals, mounted 3 m above ground,

164 while the plot was protected with a wind shield [32]. Details on the experimental procedure

165 are given in Stone et al. [33]. A dry run at initial soil moisture was followed 45 minutes later

166 by a wet or very wet run. The experiments chosen as the calibration set were wet and very wet

167 runs from 2007 and 2008 on 6 large plots (LP) of 6.1 by 2 m, with apparent steady state

168 runoff reached after application of at least 5 minutes of rainfall. These experiments were

169 chosen as the calibration set, because orthogonal photos of the plot during experiments and

170 dye velocity measurements (u, LT^{-1}) existed for them which were required for the

171 parameterization of the model (Table 1). The photos covered the lower 3 m of the runoff plot,

172 and on three transects along the plot width, w_p (L), at lengths of approximately 3.75, 4.5 and

173 5.25 m from the upper plot border, the width fraction of inundation was measured by visual

174 interpretation. Usually, it could easily be seen which parts were covered by water or not,

175 however, stone pavements protruding through a layer of water occasionally created

176 uncertainty in the visual interpretation. Runoff alternated between more concentrated faster

177 flow around vegetated mounds and broader sheetflow in between. Water often flowed along

178 the lateral plot borders. A trend towards more inundation at the lower end of the plot was not

179 present. Consequently, all three transect measurements were averaged to form a single

180 inundated area fraction (A_i), representative for the plot. Mean flow velocity was computed

181 using the centroid of the electrical resistivity curve measured at the outlet of the plot [34].

8

182 Rainfall simulations on large plots from 2004 (four plots), where no photos were taken, and

183 small plots (SP, 0.75 m^2, 3 plots) from 2008, were used as validation (Table 1).

184 Natural rainfall – runoff events were selected from a continuous period of runoff and

185 rainfall measurements from 2001 to 2010. Rainfall depth was digitally recorded at 1 min

186 increments during periods of rainfall at a gage about 100 m from the outlet of LH-106. The

187 runoff hydrograph was measured also as breakpoint data at the H-Flume (Figure 2). During

188 this period 718 rainfall events were recorded of which 60 resulted in runoff. All runoff events

189 except for one (23.07.2008) had incident rainfall totals of more than 4.5 mm. Thus, this value

190 was chosen as a minimum threshold for the selection of a dataset of rainfall events to be

191 analysed. Volumetric soil moisture content at 5 cm depth was measured at a meteorological

192 station 270 meters north of LH-106. The maximum value was taken as the effective saturated

193 soil moisture content or effective porosity, η_e (L^{3}L^{-3}) = 0.29. To obtain a relevant estimate of

194 initial soil moisture content, θ_i (L^{3}L^{-3}) a value just before rainfall started was selected for each

195 event. Five rainfall events, of which one was producing runoff (07.07.2001), had no soil

196 moisture measurements. The deletion of these events and the use of the rainfall threshold

197 resulted in a total of 147 rainfall events with 58 producing runoff (Table 1). Selecting rainfall

198 events with a threshold rather than selecting only runoff events reflects the fact that in a

199 rainfall – runoff model rainfall is an independent variable while runoff is the quantity to be

200 predicted.

201

202 [location of Table 1]

9

3 Model descriptions

Two contrasting models for the calculation of infiltration and runoff hydraulics at the local scale of a modelling unit are presented. Both were applied in a distributed model for the calculation of runoff at the small watershed-scale.

3.1 Conventional Green-Ampt model with sheet flow (CON)

The model to which the new proposed model is compared is termed conventional, because it uses equations that are commonly used to model runoff on hillslopes. Infiltrability (f_t) at the point-scale, assuming piston-type flow is given by the Green-Ampt Equation [35] [e.g. Equation 5.4.1 in 36]:

$$f_t = K_s\left(\frac{\psi\Delta\theta}{F_t} + 1\right)$$ (1)

where K_s is the point-scale hydraulic conductivity (LT^{-1}), ψ (L) is the suction across the wetting front and $\Delta\theta$ ($L^3 L^{-3}$) is the difference between η_e and θ_i. F_t is the cumulative infiltration at the end of a time step, which is given by Equation 5.4.2 in Chow et al. [36]:

$$F_t = F_{t-\Delta t} + K_s\Delta t + \psi\Delta\theta\ln\left(\frac{F_t + \psi\Delta\theta}{F_{t-\Delta t} + \psi\Delta\theta}\right)$$ (2)

The use of Equations 1 and 2 for the application to variable intensity rainstorms has been described by Chu [37]. Under the assumption of zero heterogeneity, point-scale K_s equals the

10

224 effective hydraulic conductivity K_e (LT^{-1}). When the surface becomes saturated at ponding

225 time, infiltration is assumed to occur below a thin continuous water layer covering the whole

226 modelling unit. Equally, runon that enters a modelling unit is effectively distributed over the

227 whole surface area and is added to rainfall to form a common water influx.

228   For modelling runoff on a hillslope, a roughness coefficient is required for the estimation

229 of flow depth. We chose to use Manning's n, as it can be assumed that flow either becomes

230 turbulent as it concentrates downslope, or it is laminar or intermediate, but much disturbed by

231 roughness elements such as stones or litter. The average flow depth D (L) of the whole

232 modelling unit is calculated as:

233

234
$$D = \left(\frac{n}{S^{1/2}} q_e \right)^m \tag{3}$$

235

236   where q_e (L^{2}T^{-1}) is the effective or average unit width discharge of a modelling unit, S is

237 the gradient of the water surface, assumed to be equal to the slope gradient, and m is an

238 exponent which is 0.6 for turbulent flow [38].

239   At its core, the CON model contains Chu's variable rainfall intensity Green and Ampt

240 infiltration model [37], with the main addition of the possibility of runon infiltration (r_{in})

241 (Figure 4)

242

243   [location of Figure 4]

244

11

3.2 Water depth-dependent Green-Ampt model with partial inundation (WDD)

Contrary to the sheetflow assumption, the WDD model acknowledges that there is microtopography. This means that for every level of inundation within the microtopography, there is an average water depth positively correlated to the inundation fraction A_i. The type of this relationship will depend on the microtopography. As a first approximation we used a linear relationship between the inundation fraction and water depth.

$$A_i = bD \tag{4}$$

with b an empirical constant. Equation 4 does not imply that there is a single channel per modelling unit; it is purely empirical and can contain any amount of micro-channels that can take a tortuous route. These surface and flow characteristics (e.g. flow through protruding stones in this study) are accounted for by Manning's n. As there are inundated and not inundated areas, q_e in Equation 3 should apply for the inundated area only. The average effective plot unit runoff r_e (LT^{-1}) is computed by averaging the inflow r_{in} (LT^{-1}) from upslope area and the outflow r_{out} (LT^{-1}) from a modelling unit:

$$r_e = (r_{in} + r_{out})/2 \tag{5}$$

Unit width discharge in the WDD model is for width of the inundated area only, so it is defined in relation to r_e as:

12

268 $$q_e = l_p r_e A_i^{-1} \qquad\qquad (6)$$

269

270   where l_p (L) is the length of the modelling unit. The depth-discharge relationship can now

271 be adapted for the WDD model, by substituting Equation 4 into Equation 6, which was then

272 substituted into Equation 3:

273

274 $$D = \left(\frac{n\, l_p r_e}{S^{1/2} b} \right)^{\frac{m}{1+m}} \qquad\qquad (7)$$

275

276   Hydraulic conductivities in the WDD model are assumed to have an exponential

277 distribution, an assumption that has been successfully tested elsewhere [33, 39, 40]:

278

279 $$g(K_s) = \frac{1}{\mu_K} \exp\left(-\frac{K_s}{\mu_K} \right) \qquad\qquad (8)$$

280

281   where $g(K_s)$ is the probability distribution of hydraulic conductivities on the scale of the

282 microtopography, within a modelling unit, with μ_K (LT^{-1}) their mean, which is assumed

283 constant. We did not assume a random distribution but one that is monotonically increasing

284 with relative elevation of the microtopography, which is in line with field observations (see

285 introduction). This assumption has been made before, but not in conjunction with the

286 exponential distribution [22, 25]. Hawkins [39] formalized the partial contributing area

287 approach: at any rainfall intensity (i, LT^{-1}), there is always some area where rainfall intensity

288 is limiting infiltration and some area where the soil's infiltration capacity is limiting

289 infiltration, the latter termed runoff contributing area fraction (A_c). In the small-scale context

13

290   of the microtopography, A_c can be interpreted as the area where water flows erratically,

291   depending on actual raindrop impact towards an inundated area (Figure 5a). When rainfall

292   starts, A_c is infinitely small, but once soil suction decreases and rainfall intensity increases, a

293   substantial area fraction can contribute to runoff production (Figure 5a). When water

294   accumulates and concentrates further downstream, or when there is a sudden decrease in

295   rainfall intensity during or at the end of a storm, the accumulated water can inundate an area

296   bigger than A_c (Figure 5b). In this case runon infiltration will occur on the inundated area.

297   Figure 5a and b depict a single channel for clarity of the illustration, but the generalized

298   model (Equation 4) does not require a specific microtopography form.

299

300   [location of Figure 5a and 5b]

301

302   In the case of an exponential distribution with a single mean parameter, and when ψ and

303    $\Delta\theta$ are spatially constant, the mean infiltration capacity μ_f (LT^{-1}) is proportional to μ_K, just like

304   f_t is proportional to K_s (Equation 1) on the point-scale:

305

$$\mu_f = \mu_K \left(\frac{\psi \Delta \theta}{F_t} + 1 \right) \qquad (9)$$

307

308   Equation 9 assumes that there is sufficient horizontal redistribution of infiltrated water to

309   form a single infiltration front. It has been shown that an average Green-Ampt infiltration

310   front produced results close to a three-dimensional finite difference solution [41]. F_t, the

311   cumulative infiltration of the time step is not known when it is required in Equation 9, so the

312   cumulative infiltration of the previous time step $F_{t-\Delta t}$ (with Δt being the time interval) is used

313   as an initial guess (Figure 6). During subsequent iterations within the time step the value of F_t

314   is updated.

315

316   [location of Figure 6]

317

318   Equation 9 yields μ_f which is necessary for the calculation of A_c. As A_c is defined as the

319   area fraction where the infiltration capacity is less than the rainfall intensity i, it is obtained by

320   integrating the exponential distribution of infiltration capacities g(f) from 0 to i which yields:

321

322    $$A_c = \int_0^i g(f)df = 1 - \exp\left(-\frac{i}{\mu_f}\right)$$ (10)

323

324   where g(f) is the same as g(K_s) in Equation 8, only that μ_K is substituted with μ_f. Like A_c, A_i is

325   also a function of the exponential distribution:

326

327    $$A_i = \int_0^{K_s(A_i)} g(K_s)dK_s = 1 - \exp\left(-\frac{K_s(A_i)}{\mu_K}\right)$$ (11)

328

329   where $K_s(A_i)$ is the hydraulic conductivity at the edge of the water level of inundation.

330   Similarly, $K_s(A_c)$ is the hydraulic conductivity at the edge of the runoff contributing area.

331

332    $$K_s(A_{c|i}) = -\ln(1 - A_{c|i})\mu_K$$ (12)

333

15

334   Where $A_{c/i}$ is either A_c or A_i. The average hydraulic conductivity of the runoff

335   contributing area K_c and the average hydraulic conductivity of the inundated are K_i are

336   obtained by integrating hydraulic conductivities from the exponential distribution $g(K_s)$ from

337   0 to $K_s(A_{c/i})$, which yields:

338

$$K_{c|i} = \int_0^{K_s(A_{c|i})} K_s g(K_s) dK_s = \mu_K - \left(1 - A_{c|i}\right)\left(\mu_K + K_s(A_{c|i})\right), \tag{13}$$

340

341   Where $K_{c|i}$ is either K_c or K_i. F_t can now be calculated as:

342

$$F_t = F_{t-\Delta t} + i\Delta t\left(1 - A_{c|i}\right) + A_{c|i}\left(K_{c|i}\Delta t + \psi\Delta\theta \ln\left(\frac{F_t + \psi\Delta\theta}{F_{t-\Delta t} + \psi\Delta\theta} \right)\right) \tag{14}$$

344   .

345   with $A_{c|i} = A_i$ and $K_{c|i} = K_i$ if $A_i > A_c$ (case Figure 5b), and else $A_{c|i} = A_c$ and $K_{c|i} = K_c$ (case

346   Figure 5a). Equation 14 is derived from Equation 2, splitting the cumulative infiltration into a

347   part where rainfall infiltrates directly (the second term) and a part where infiltration during a

348   time step under A_i or A_c is limited by the soil (the third term). The resulting value of F_t is still

349   an approximation and the calculation of Equations 9 to 14 are repeated until F_t used in

350   Equation 9 differs from the outcome in Equation 15 by less than a very small threshold value.

351   The effective infiltration rate f_e (LT^{-1}) of the modelling unit is now given by:

352

$$f_e = i\left(1 - A_{c|i}\right) + K_{c|i}\left(\frac{\psi\Delta\theta}{F_t} + 1\right)A_{c|i}. \tag{15}$$

354

16

355   The first term is infiltration equal to rainfall intensity on the non-inundated and no runoff

356   producing part of the soil and the second term describes infiltration according to the Green-

357   Ampt equation on the remaining inundated or runoff producing area.

358

3.3 2D distributed Model

360   Both infiltration models are implemented in MCST [47], a spatially distributed runoff-erosion

361   model that originally used a modified curve number approach. The model routes runoff using

362   the kinematic wave equation in conjunction with a flux decomposition algorithm [43] [48].

363   A digital elevation model of the watershed with a 1 m horizontal resolution from a RTK

364   GPS survey with 426 elevation points was used [42]. Infiltration and runoff calculation was

365   changed so that runon infiltration could be accounted for in each grid cell and at each time

366   step. Following the logic of the linear scheme of the kinematic wave algorithm, r_e in Equation

367   5 was calculated with r_{in} as inflow into a modelling unit during the present time step and r_{out}

368   as the outflow calculated on the same modelling unit during the previous time step. In the

369   CON model the estimate of r_e was added to the rainfall intensity to calculate the amount of

370   water which was available for infiltration on the whole surface of the modelling unit in

371   accordance with the sheet flow assumption. In the WDD model, r_e was used to calculate D

372   (Equation 7) and A_i (Equation 4) and then infiltration as described above. For a given set of

373   parameter values controlling infiltration the WDD model will always predict lower runon

374   infiltration for the same runon amount, unless there is full inundation. Once infiltration is

375   calculated in both models, an estimate for the net lateral inflow into a modelling unit during a

376   time step, Δr (LT^{-1}), is obtained, which can become negative during runon infiltration, and is

377   given by the difference between rainfall intensity and infiltration. It relates to the kinematic

378   wave equation as:

17

379

$$\frac{\partial\left(r_{out}l_p\right)}{\partial l_p} + \frac{\partial D}{\partial t} = \Delta r = i - f_e \tag{16}$$

381

382   Equation 17 was solved using a discrete non-linear scheme [36]. So for each time step

383   and modelling unit, runoff, infiltration, water depth, and in the case of the WDD model,

384   inundated area fraction are estimated. For a single rainfall event, three main output quantities

385   were calculated that could be compared to measured quantities: the total discharge, Q_t (L^3),

386   which is the sum of discharge of all time steps at the modelling unit (cell) that represents the

387   outlet of the watershed. The steady state effective discharge, Q_e (L^3T^{-1}), is a quantity that is

388   used in erosion modelling, also in the MCST model, and is given by [43]:

389

$$Q_e = \left(\frac{\sum_{t=t_1}^{t_n} Q^{1.4}}{\sum_{t=t_1}^{t_n} Q}\right)^{2.5} \tag{17}$$

391

392   where Q (L^3T^{-1}) is the discharge during one time step t, with t_1 the first and t_n the last

393   time step of an event. The third quantity is peak discharge, Q_p, (L^3T^{-1}). All three quantities

394   can be modelled and also derived from observational hydrographs, measured at the H-flume

395   at the watershed outlet.

396

3.4 Model parameterization and evaluation

In accordance with the second objective, the model was parameterized using the calibration set of rainfall simulations to find values for K_e and μ_K for the CON and the WDD model, respectively, and values of Manning's n and the parameter b, the latter for the WDD model. Secondly, K_e, μ_K, ψ and n were calibrated for natural rainfall-runoff events by optimizing an objective function consisting of the Nash-Sutcliffe model efficiency (ME) and the coefficient of determination (R²) of predictions of Q_t, Q_e and Q_p, where R² was defined as:

$$R^2 = ME = 1 - \frac{\sum_{i=1}^{n}(X_{observed} - X_{predicted})^2}{\sum_{i=1}^{n}(X_{observed} - X_{mean})^2} \tag{18}$$

where X is the quantity of interest. When equation 19 is used to calculate ME, X is the instantaneous runoff rate during a time step. All parameters were assumed to be constant within the catchment.

3.4.1 Parameterization using rainfall simulations

An estimate of average plot width flow depth on the rainfall simulation plots (assuming sheet flow) was obtained for the CON model using measured average velocities:

$$D = \frac{r_e l_p}{u} \tag{19}$$

19

417　where r_e was calculated from Equation 5 with measured r_{out} and zero r_{in}. This allowed to

418　find a value for Manning's n that minimized the square of the residuals between predicted and

419　measured D, using observed D, r_e and S data (least squares method) (Equation 3).

420　For the WDD model, D is defined for the inundated area only, so Equation 20 becomes:

421

$$D = \frac{r_e l_p}{u A_i} \tag{20}$$

423

424　A_i values were measured as described in section 2.2. D in Equation 21 was substituted

425　with A_i/b (Equation 4) and then b was optimized with the least squares method for predicted

426　and measured r_{out}. Similarly to the CON model, Manning's n could now be found with the

427　least squares method (Equation 7).

428　As K_e was assumed to approximately equal measured final infiltration rates during the

429　(wet run) rainfall experiments, for the CON model an estimate of average K_e is simply derived

430　by averaging final infiltration rates of the calibration dataset. For the WDD model, μ_K was

431　optimized as described and depicted in Figure 9, dashed area, in Langhans et al. [27] for the

432　steady state case of the rainfall simulation plots.

433

3.4.2 Calibration on multiple rainfall events

435　The dataset of 147 rainfall events (Table 1) was randomly split into a calibration set of 74

436　events and a validation set of 73 events. In accordance with objective 3, optimized parameter

437　sets were found for the CON and the WDD model from the calibration set to assess the water

438　depth-dependency effect, and for both models parameter sets were found that assess the effect

20

439   of runon infiltration. For the CON model this was done by forcing r_{in} to be zero during

440   infiltration calculation, and for WDD this was done by forcing A_i to be zero during infiltration

441   calculation. The objective function (OBJ) was defined as:

442

443   $$OBJ = \left(ME + \left(R^2(Q_t) + R^2(Q_e) + R^2(Q_p)\right)/3\right)/2 \qquad (21)$$

444

445   In words, during optimization, the mean R^2 of the predictions of total, effective, and peak

446   discharge was given equal weight as ME. For CON, ψ, K_e and Manning's n, and for WDD ψ,

447   μ_K and Manning's n were simultaneously optimized using the following simple set search

448   method. Starting values within realistic bounds were chosen, and parameter combinations

449   were added that were half the starting value's step in each direction of the parameter space

450   (with three calibration parameters, this results in a 3D grid, when visualized). For each

451   parameter combination in the set, OBJ was calculated, and the combination with the largest

452   value was chosen. This combination was used as a new starting point for another set search,

453   but with half a step size compared to the previous iteration. The number of iteration was

454   limited by computation time but usually exceeded 4. It was ensured that OBJ were indeed

455   maximized within the search space by plotting OBJ. The accuracy was between 1-5 mm for

456   ψ, 0.5 mm/h for K_e and μ_K, and 0.002 for Manning's n.

457

4   Results

4.1   Rainfall simulations

460   Water depth of the inundated area show has a clear positive relationship with effective

461   discharge (WDD, Figure 7), with little scatter for the year 2007. Also, 2007 water depth

21

462   values are much higher than values of plots from 2008, while the latter level off at 0.002-

463   0.003 m at high flow rates. The $D - r_e$ relationship under the sheet flow assumption (CON,

464   Figure 7) shows more scatter and lower depth estimates at higher flow rates, as can be

465   expected, because flow is spread over the whole plot. The relationship of $A_i - r_e$ (not shown)

466   gives the same picture as WDD depths in Figure 7, because A_i and D are related only with the

467   proportionality parameter b. The range of measured inundation fractions was 0.1 to 0.7.

468   Values for Manning's n were 0.26 and 0.57 for CON and WDD, respectively.

469

470   [location of Figure 7]

471

472   Final infiltration rates (K_e) in the years 2007 and 2008 were much higher than they were

473   in 2004, which were used as validation data (Figure 8). K_e on the small plots in 2008 were

474   more closely in the range of the infiltration values on the long plots. Moreover, K_e showed a

475   stronger dependency on rainfall intensity in 2007 and 2008 than in 2004. Average K_e, used in

476   the CON model is a constant at 57.2 mm h^{-1}, while μ_K (WDD) was optimized at 62.4 mm h^{-1}

477   (Table 2). In order to clarify the models' behaviour on the rainfall simulation plot-scale, final

478   infiltration rates were modelled for a range of rainfall intensities for the 6 m plot, with an

479   average slope of 0.14. The WDD model predicts that the inundation effect (infiltration in area

480   where A_i exceeds A_c) is strongest around the mean of the distribution on the 6 m plot (solid

481   line departing from dash-dotted line in Figure 8). For the 1 m plots the curve for the average

482   predicted K_e lies much closer to the curve of the dashed line, because, relatively, less runon

483   infiltration occurs on a shorter slope (line not shown). Calculated complete inundation at

484   higher rainfall intensities is a bias produced by the assumption of a linear relationship

22

485 between average water depth and inundation. Actually, there are always some parts of the

486 plot, such as mounds under creosote bushes that remain un-inundated.

487

488   [location of Figure 8] [location of Table 2]

489

490   Final infiltration rates on long plots were much lower during 2004 (validation), and both

491 models had negative R². For the small plots (2008), however, the WDD model yielded better

492 predictions (R² = 0.86) compared to the CON model (R² = 0.10).

493

4.2 Calibration with rainfall-runoff events

495   Parameter values derived from rainfall simulations were used to model runoff

496 hydrographs of all 147 rainfall events. With hardly any runoff predicted, both models

497 performed poorly, with negative R² (Equation 19) (results not shown). Calibration on multiple

498 events at field-scale yielded much lower optimized values for K_e and μ_K, both for model runs

499 with and without runon infiltration (Table 2). Also, Manning's n values were much smaller

500 than the rainfall experiments suggested. Optimized ψ values were much higher for the WDD

501 than the CON model. The optimization process during calibration yielded clearly defined

502 maxima and smooth contours for OBJ in the parameter space for both models (Figure 9).

503

504   [location of Figure 9 a-d]

505

506   For the calibration set 37% of rainfall-runoff events for both, CON and WDD, had ME

507 values above 0.75 (Table 3). The WDD model however had a higher proportion of events

508 above 0.75 for the validation set. Coefficients of determination for Q_t, Q_p, and Q_e were good

23

509   for all models and OBJ values were slightly higher for the WDD model than the CON model.

510   The CON model performed slightly better in validation with runon infiltration than without

511   runon infiltration. Comparing observed vs. predicted Q_t revealed that CON had too many

512   events predicting no runoff where there was runoff observed, and, conversely, the WDD

513   model always predicted some runoff, leading to slight overestimation at low runoff rates

514   (figure not shown).

515

516   [location of Table 3]

517

518   4.3 Model behaviour

519   Model behaviour was further studied by comparing predictions of hydrographs with

520   actually observed hydrographs, and by exploring the effects of water depth-dependency and

521   runon infiltration through calculating infiltration under a steady rain (Figure 10). For a 40 mm

522   h^{-1} synthetic rainstorm of 30 minutes, the average watershed-scale infiltration rate for the

523   CON model was equal to rainfall intensity for the first 10 minutes, after which it dropped to

524   below 23 mm h^{-1} at 30 minutes. When allowing runon infiltration, substantial runon

525   infiltration occurred with the CON model between 30 and 40 minutes. For the WDD model

526   infiltration rates dropped immediately after onset of rainfall to below 20 mm h^{-1} at 30

527   minutes. When accounting for runon infiltration, infiltration rates of WDD are only less than

528   0.5 mm h^{-1} larger from minute 8 onwards compared to WDD without runon infiltration, and

529   after 30 minutes runon infiltration drops immediately to 1.5 mm h^{-1} only. Water depth-

530   dependent infiltration under such a scenario is thus negligible, whereas runon infiltration in

531   the CON model is important.

532

24

533   [location of Figure 10]

534

535   For qualitative analysis of the goodness of hydrograph prediction with the watershed-

536   scale calibration parameters, six events were chosen and displayed: The 90th, 50th, and 10th

537   percentile event, based on descending ranking of ME, both for CON and WDD, with runon

538   (Figure 11).

539

540   [location of Figure 11]

541

542   For the 90th percentile events, the timing of the peak and peak discharge were better

543   predicted for CON than WDD (Figure 11 a and b). For the 50th percentile events, peak

544   discharge was predicted better with the WDD model (Figure 11, c and d), but timing was

545   either worse (Figure 11 c) or better (Figure 10 d) than CON. For the 10th percentile, WDD had

546   a stronger over estimation of peak discharge than CON (Figure 11 e and f), and timing was

547   not apparently wrong. Regarding the form of the hydrographs, WDD generally has a steeper

548   rise than CON, and follows rainfall intensity more closely. CON hydrographs are usually

549   slightly better timed. Generally, however, over- or under-predictions of total or peak

550   discharge not systematic, except, perhaps a tendency of WDD to over-predict during small

551   events and under-predict during larger events.

552

25

5 Discussion

5.1 The role of rainfall simulations in watershed-scale models

555   Rainfall simulation is a widely used tool to infer local scale infiltration parameters and

556 characteristics. Orthogonal photos are an excellent way to gather additional information about

557 runoff characteristics, like inundation and flow paths relative to microtopography. The

558 method of deriving inundated area fractions is particularly useful, because they can be directly

559 linked to depth-discharge relationships (Equations 4 and 7). Despite some inter year

560 variability, calculated depths and effective runoff show a clear relationship (Figure 7). The

561 range of average depth values ($< 1 - 7$ mm) lies within the range that Abrahams and Parsons

562 [44] measured at a similar site on the WGEW. Direct, high precision measurements of runoff

563 water depth [45] or combined inundation and microtopographical measurements for the

564 calculation of water depth are surely superior to inference from flow velocity. However, even

565 in the absence of more direct depth measurements, taking inundation into account will yield

566 more realistic average water depths than the sheet flow assumption, because flow on a small

567 scale hardly ever covers the whole surface where microtopography is present [46].

568   Values of Manning's n calibrated from the natural rainfall-runoff events were lower with

569 a factor of 3 for the CON model and 19 for the WDD model compared to values derived from

570 rainfall simulations, and K_e and μ_K were four to five times lower (Table 2). There are several

571 possible explanations for this discrepancy, but none taken on its own is sufficient. Regarding

572 hydraulic roughness, it was observed from the orthogonal photos that plot borders impeded

573 flow around mounds of creosote bushes. This must have led to more inundation and higher

574 water depths than would occur in a natural setting without plot borders, where flow can

575 follow unimpeded low lying channels between mounds. This means that on the plot average

576 flow velocities were lower and Manning's n higher than in a natural setting. Certainly, the

26

577 plot borders increase ponding and with it final infiltration rates during rainfall simulations, but

578 it is unlikely that the effect can explain a four to five -fold difference. Runoff experiments in

579 2004 still had roughly 2.5 times higher final infiltration rates than the calibrated values.

580 Higher infiltration rates are a common observation for rotating or oscillating boom rainfall

581 simulators. Risse et al. [47] and Nearing et al. [48] have reported 2-4 times higher K_e for

582 rainfall simulations than calibrated values from runoff measurements on larger scale for

583 humid environments. Burns [49] reported for the WGEW site 3-6 times higher rainfall

584 simulation derived K_e than were calibrated for the small watershed-scale. The source of this

585 discrepancy has not been reported. Beside the plot border effect, we can briefly point out three

586 areas of explanation that can contribute to the difference. First, the oscillating boom rainfall

587 simulator has intermittent, very high rainfall intensities with no rainfall in between. According

588 to the partial area response concept, during the high rainfall intensity bursts, high infiltration

589 rates can be achieved, while only time-averaged rainfall intensity is reported that would lead

590 to a much lower infiltration rate. Secondly, there could be a bias during rainfall simulation

591 site selection towards higher infiltration 'interrill' areas. Finally, during rainfall simulations

592 air can escape laterally, which is not possible under natural rainfall which covers the whole

593 area.

594 As infiltration was higher on the small rainfall simulation-scale, scale effects were the

595 inverse of what one would expect from runon-infiltration theory. But given the above-

596 mentioned differences between rainfall simulations and watershed-scale natural rainfall runoff

597 measurements that can possibly affect infiltration rates, it can be concluded that the two types

598 are incomparable for the purpose of scale enquiry, at least under the studied conditions and

599 environment. This implies that rainfall simulations cannot simply be used for the

600 parameterization of any of the two predictive models, which is confirmed by their bad

601 performance when parameterized with rainfall simulation data in this study. Nevertheless,

27

602 rainfall simulations can be a valuable tool to study depth-discharge relationships, and relative

603 differences of infiltration between sites and environments, or indeed to study any sub-

604 processes of infiltration in more detail.

605

5.2 Importance of water depth-dependency and runon infiltration

607   Both models can predict hydrographs satisfactorily when calibrated on the watershed-

608 scale (Table 3). The water depth-dependent model (WDD) performs slightly better than the

609 conventional sheet flow model (CON), but this improvement is not related to the inundation

610 effect, as the effect is probably very small when parameterized with a relatively low

611 Manning's n of 0.028 (Figure 10). Possibly, the main improvement above CON stems from

612 the responsiveness of runoff to rainfall, because WDD contains a distribution of hydraulic

613 conductivities, where low conductivities already respond with runoff production at low

614 rainfall intensities. For the CON model, the inclusion of runon infiltration improves

615 performance slightly (Table 3). This supports the theoretical importance of runon infiltration

616 pointed out already by other researchers [10, 13].

617   There are three model structural reasons and one physical reason why water depth-

618 dependent infiltration and runon infiltration does not show up to be important in the WDD

619 model in this study. First, Langhans et al. [27] have shown in a synthetic study that scale

620 effects due to the water depth effect can be significant, but they used a relatively high

621 hydraulic roughness value derived from rainfall simulations. In this study, hydraulic

622 roughness is relatively low, and significant water depths that cause water depth-dependent

623 infiltration do not build up. The physical reason, related to this, is that the macrotopography in

624 the study catchment is very rugged so that runoff concentrates very quickly in channels and

625 the effective hillslope lengths are very short; water depth cannot build up sufficiently on such

28

626 short slopes. The second model structural reason is that the exponential distribution assumed

627 here (Equation 8) is such that only at high inundation levels significant infiltration can occur.

628 If a different distribution had been chosen the water depth effect could have been more

629 pronounced, such as the log-normal distribution which had been suggested before for

630 variation of K_{sat} at larger scales [50-52]. But the analytical solution of the concept described

631 here (i.e. Equations 8 – 16) is not applicable to all distributions and it would require a more

632 stochastic, quasi-empirical approach to formulate the model with empirical or more complex

633 distributions. The third model structural reason is that the assumption that hydraulic

634 conductivities are strictly monotonously increasing within the microtopography is probably

635 too strict. Some randomness within a modelling cell, and between would increase the chance

636 of runon infiltration. A full study of various model structure-related effects, such as the choice

637 of distribution, cell resolution, or randomness would be desirable but is beyond the scope of

638 this study, as most would require a significant reformulation of the model. Consequently, and

639 despite strong theoretical justification of the water depth-dependent infiltration process as

640 pointed out in the introduction, the evidence for the water depth effect remains inconclusive

641 from this study. Future research into the water depth effect and runon infiltration should

642 therefore occur under more controlled field conditions that are tailored to quantify locations

643 and flow pathways during infiltration. Only then it is reasonable to include these effects into

644 models for prediction purpose.

645

6 Conclusions

647 The pattern of high infiltrability areas on mounds underneath shrubs and lower lying low

648 infiltrability areas in the inter-shrub area has previously been demonstrated for semi-arid

29

649 rangeland. Within the concept of water depth-dependent infiltration, runoff accumulation

650 further downslope leads to increased water depth inundating high infiltrability areas, which

651 increases the area average infiltration rate, one of many explanations for observed scale

652 effects in runoff and erosion. A model was developed that combines the concepts of water

653 depth-dependent infiltration, partial contributing area under variable rainfall intensity, and the

654 Green-Ampt theory for point-scale infiltration. The model was applied to rainfall simulation

655 data and natural rainfall − runoff data from a small semiarid watershed (0.4 ha) in the US

656 Southwest. The model performance was compared to the performance of a conventional

657 Green-Ampt model with the sheet flow assumption. Both models were parameterized with

658 rainfall simulation data, and by calibration from watershed-scale runoff measurements.

659 Parameters of hydraulic roughness and conductivity were larger by a high multiple for the

660 former compared to the latter. This implies that scale effects were the inverse of the

661 expectation, and rainfall simulation plot-scale data could not be used to successfully predict

662 hydrographs. Calibrated models both had good performance, with the water depth-dependent

663 model being slightly better. While runon infiltration was important in improving performance

664 of the sheet flow assumption model, water depth effect was negligible in the new model. This

665 was explained with rigid assumptions in the model structure, low hydraulic roughness, and

666 short hillslopes. The proposed model makes some theoretical advancement towards a less

667 scale-dependent way of modelling runoff and erosion on the hillslope-scale, but when

668 calibrated on the watershed-scale, these structural changes bring little predictive gain.

669

Acknowledgements

31

678 Notation

679 A_c rainfall excess contributing area fraction, -

680 A_i flow inundated area fraction, -

681 b empirical factor of the inundation-depth relationship, L^{-1}

682 CON   conventional Green-Ampt model with sheet flow

683 D average water depth, L

684 Δr unit area net inflow, LT^{-1}

685 Δt time step, T

686 $\Delta \theta$ difference between initial and saturated volumetric moisture content, $L^3 L^{-3}$

687 η_e effective soil porosity, $L^3 L^{-3}$

688 f_e effective infiltration rate, LT^{-1}

689 f_t potential infiltration rate or infiltrability, LT^{-1}

690 F_t cumulative infiltration at the end of a time step, L

691 i rainfall intensity, LT^{-1}

692 K_c average hydraulic conductivity of runoff contributing area, LT^{-1}

693 K_e effective hydraulic conductivity, LT^{-1}

694 K_i average hydraulic conductivity of inundated area, LT^{-1}

695 K_s point-scale saturated hydraulic conductivity, LT^{-1}

696 l_p plot length or modelling unit length, L

697 LP   Large plot

698 m exponent of depth-discharge relationship representing turbulence of flow, -

699 ME   Model efficiency, -

700 μ_f mean of distribution of infiltrabilities, LT^{-1}

701 μ_K mean of distribution of K_s, LT^{-1}

32

702	n	Manning's roughness coefficient, -
703	OBJ	objective function, -
704	P	total precipitation of an event, L
705	ψ	suction across the wetting front and $\Delta\theta$, L
706	Q	discharge during time step, $L^3 T^{-1}$
707	q_e	unit flow width discharge, plot length–averaged, $L^2 T^{-1}$
708	Q_e	steady state effective discharge, $L^3 T^{-1}$
709	Q_p	peak discharge, $L^3 T^{-1}$
710	Q_t	total discharge, L^3
711	R^2	Coefficient of determination, -
712	r_e	rainfall and runon excess or unit area flow rate, plot-averaged, LT^{-1}
713	r_{in}	unit area inflow rate at upper plot boundary, LT^{-1}
714	ρ_b	bulk density, ML^{-3}
715	r_{out}	unit area outflow rate at lower plot boundary, LT^{-1}
716	S	slope gradient, -
717	SP	small plots
718	t	time,
719	θ_i	initial volumetric soil moisture content, before start of rain, $L^3 L^{-3}$
720	θ_w	volumetric soil moisture content, $L^3 L^{-3}$
721	u	average runoff velocity, LT^{-1}
722	WDD	water depth-dependent Green-Ampt model with partial inundation
723	w_p	plot width, L

33

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36

866   Figure captions

867

868   Figure 1: Location of the study site in the southwest United States

869   Figure 2: Contour map of watershed LH- 106 in the Lucky Hills Study Area (Figure 1) with a

870   0.2 m contour interval. The background is a panchromatic Quickbird image from 7. July

871   2010. Geographic coordinates of the centre of the catchment are 31°44'32''N, 110°03'14''W

872   Figure 3: Creosote bush on mound and stony inter-shrub area.

873   Figure 4: Flow chart of the CON model and the calibration procedure with multiple rainfall

874   events. Numbers in brackets refer to Equations.

875   Figure 5a: Schematic representation of a surface unit during the beginning and middle phase

876   of a rainstorm, when $A_c > A_i$. Rainfall excess erratically flows down the microtopographic

877   slope towards the low conductivity area where inundation starts.

878   Figure 5b: Schematic representation of a surface unit during the recession or directly after a

879   rainstorm in an area where runoff concentrates or accumulates, where inundated area (A_i)

880   dominates infiltration.

881   Figure 6: Flow chart of the WDD model and the calibration procedure with multiple rainfall

882   events. Numbers in brackets refer to Equations.

883   Figure 7: Relationship between average water depth and effective discharge for 2007 and

884   2008 on the rainfall simulation plots. In the CON model water depth is calculated for the

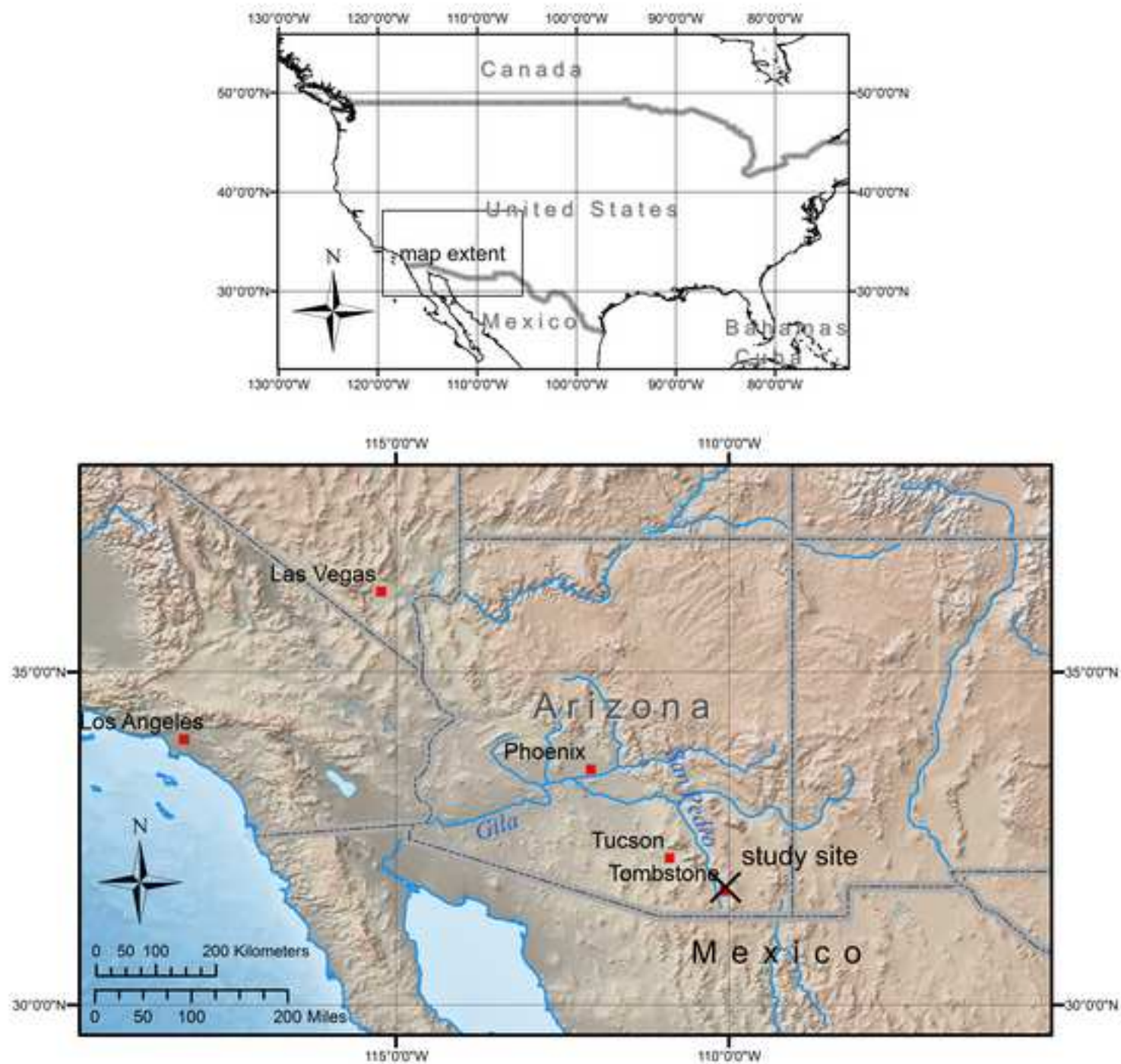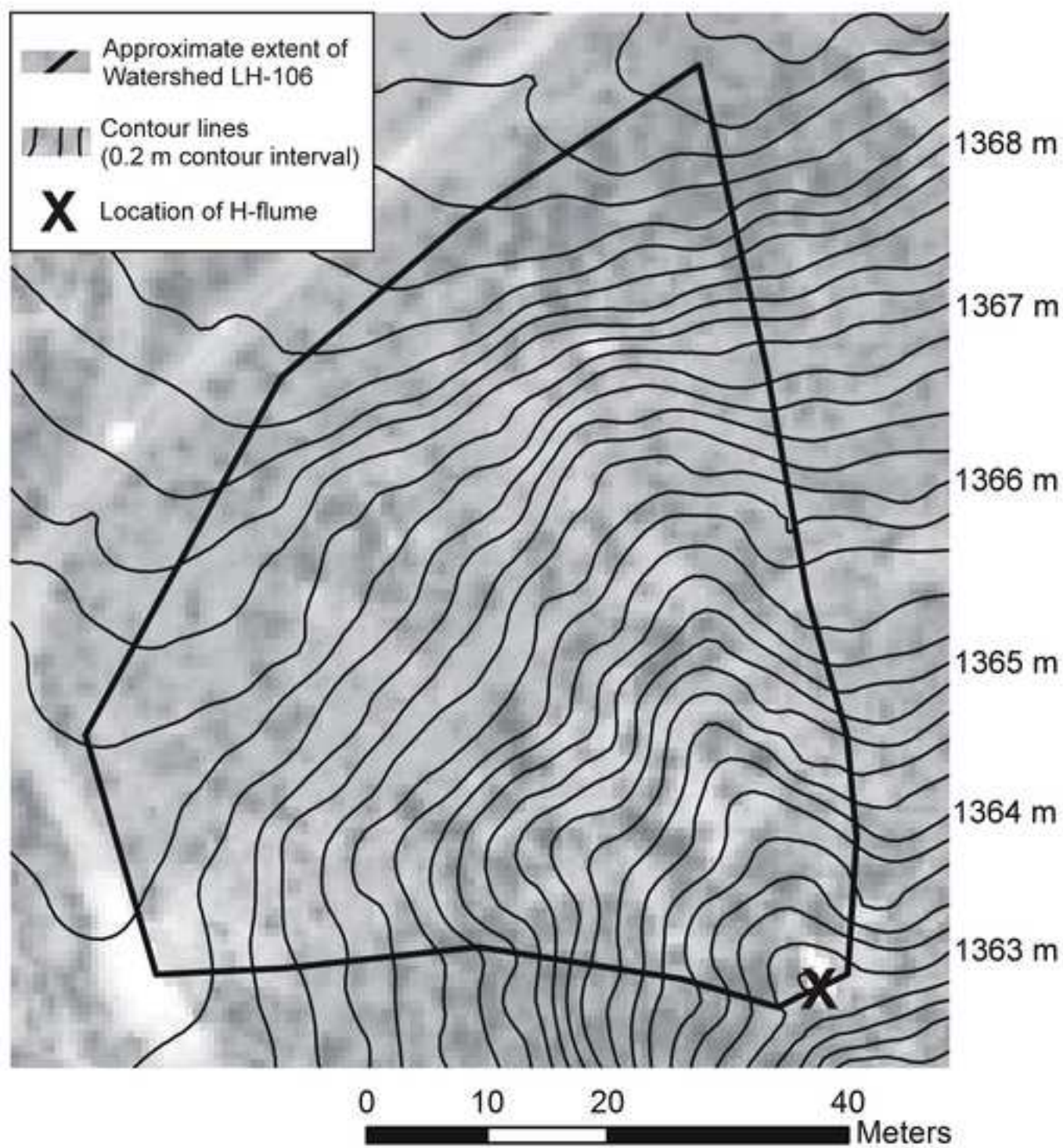885   whole plot width, while in the WDD model it is calculated for the inundated area only.

886 Figure 8: Relationship between observed final infiltration rates and rainfall intensity under

887 simulated rainfall. Lines are modelled averages of the CON model (dotted), the WDD model

888 without runon infiltration (dashed), and the WDD model with runon infiltration (solid).

889 Figure 9: Contour plots of the OBJ value in the parameter space: a) Manning's n vs. K_e for

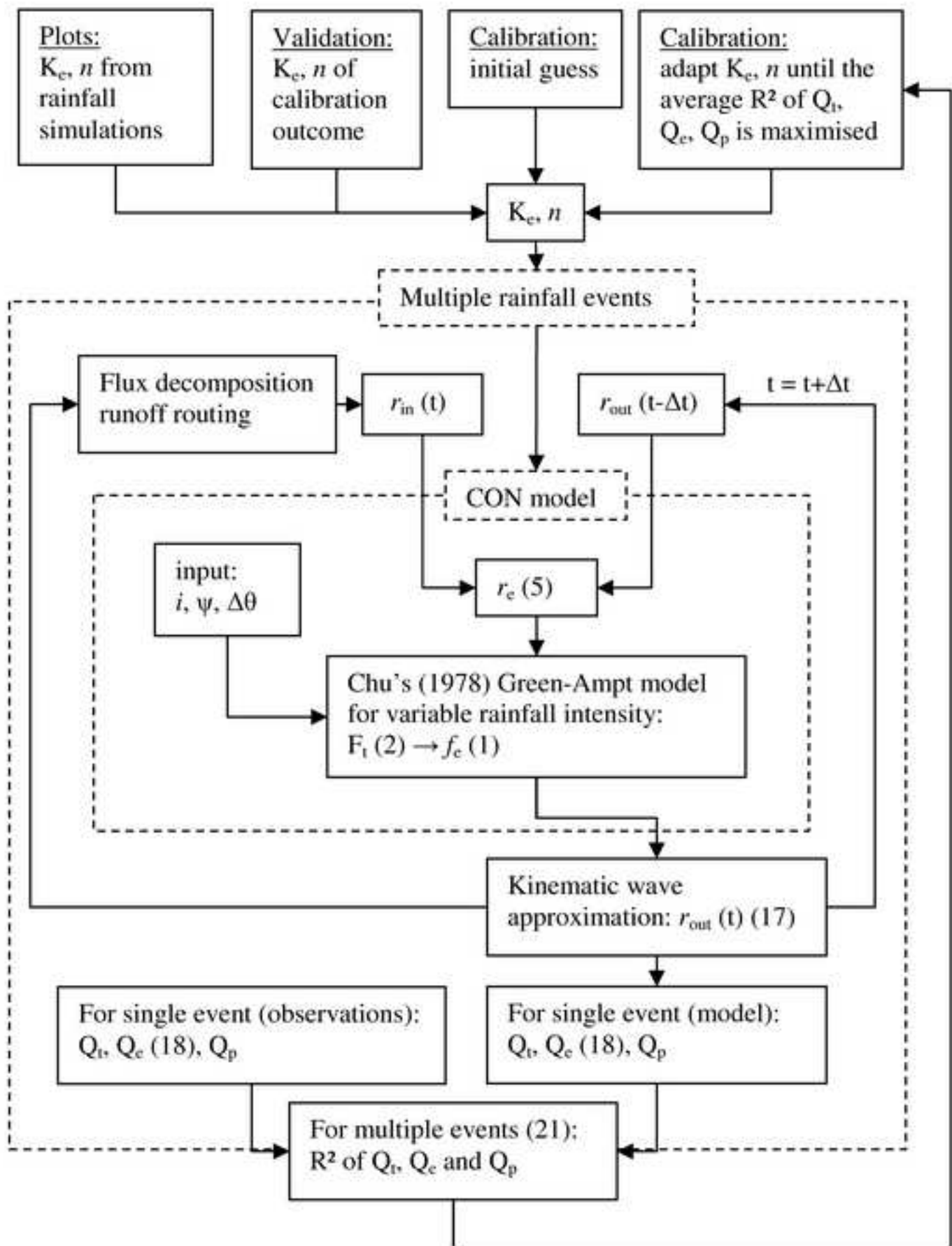890 CON, b) ψ vs. K_e for CON, c) Manning's n vs. μK for WDD, d) ψ vs. μK for WDD

891 Figure 10: Catchment average infiltration rate vs. time for a synthetic 30 min storm with 40

892 mm h-1 rainfall intensity. Infiltration rates of the WDD model with runon infiltration (solid)

893 and without runon infiltration (dotted), and of the CON model with runon infiltration

894 (dashed) and without runon infiltration (dash-dotted) are shown.

895 Figure 11: Modelled and observed hydrographs of the 90th (a: CON, b: WDD) 50th (c: CON,

896 d: WDD) and 10th (e: CON, f: WDD) percentile events based on descending ranking of ME

897 for the CON and the WDD models. Observed hydrographs are solid-shaded and modelled

898 hydrographs are dashed (WDD) and dash-dotted (CON). Rainfall intensity is displayed as

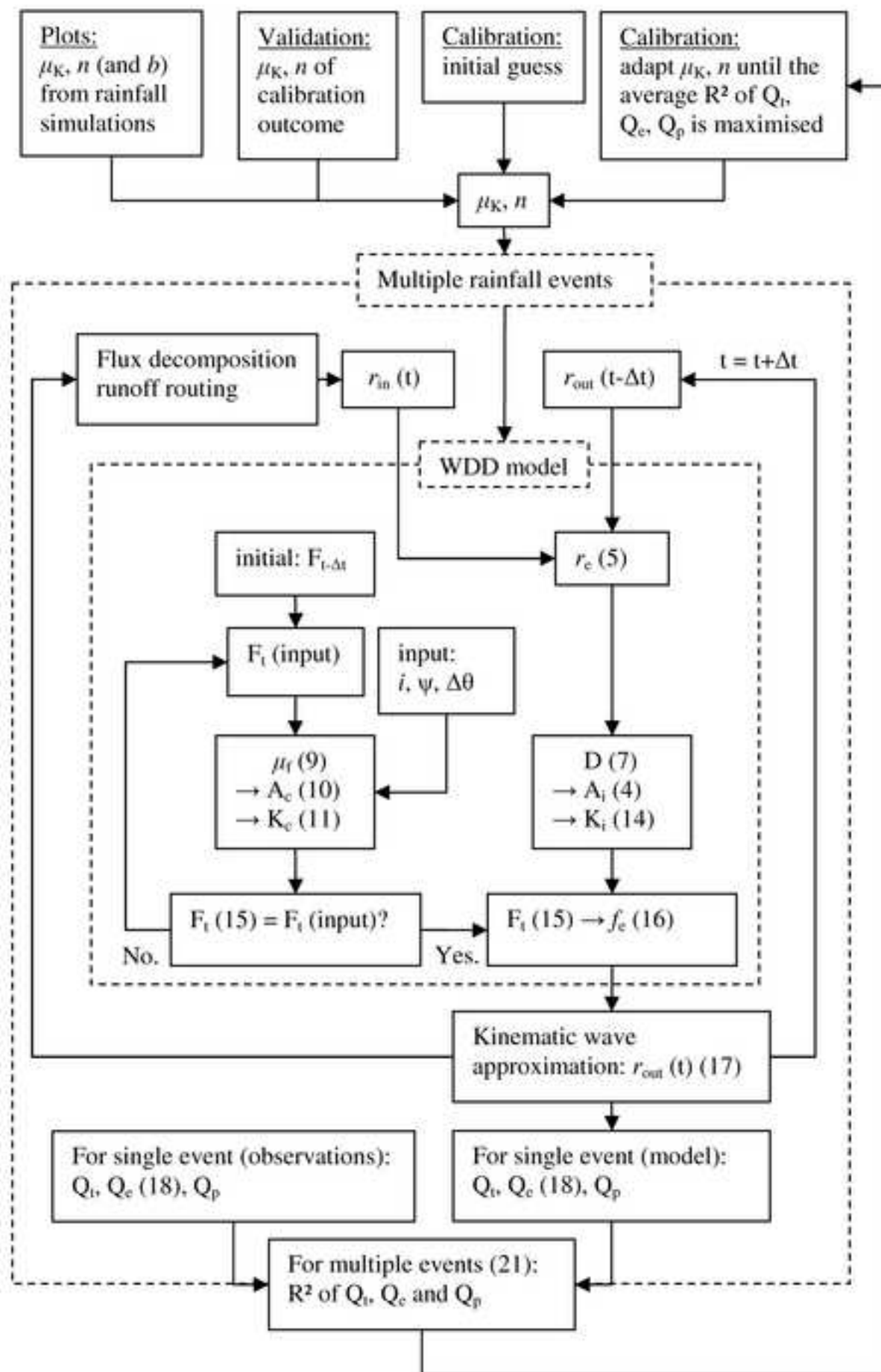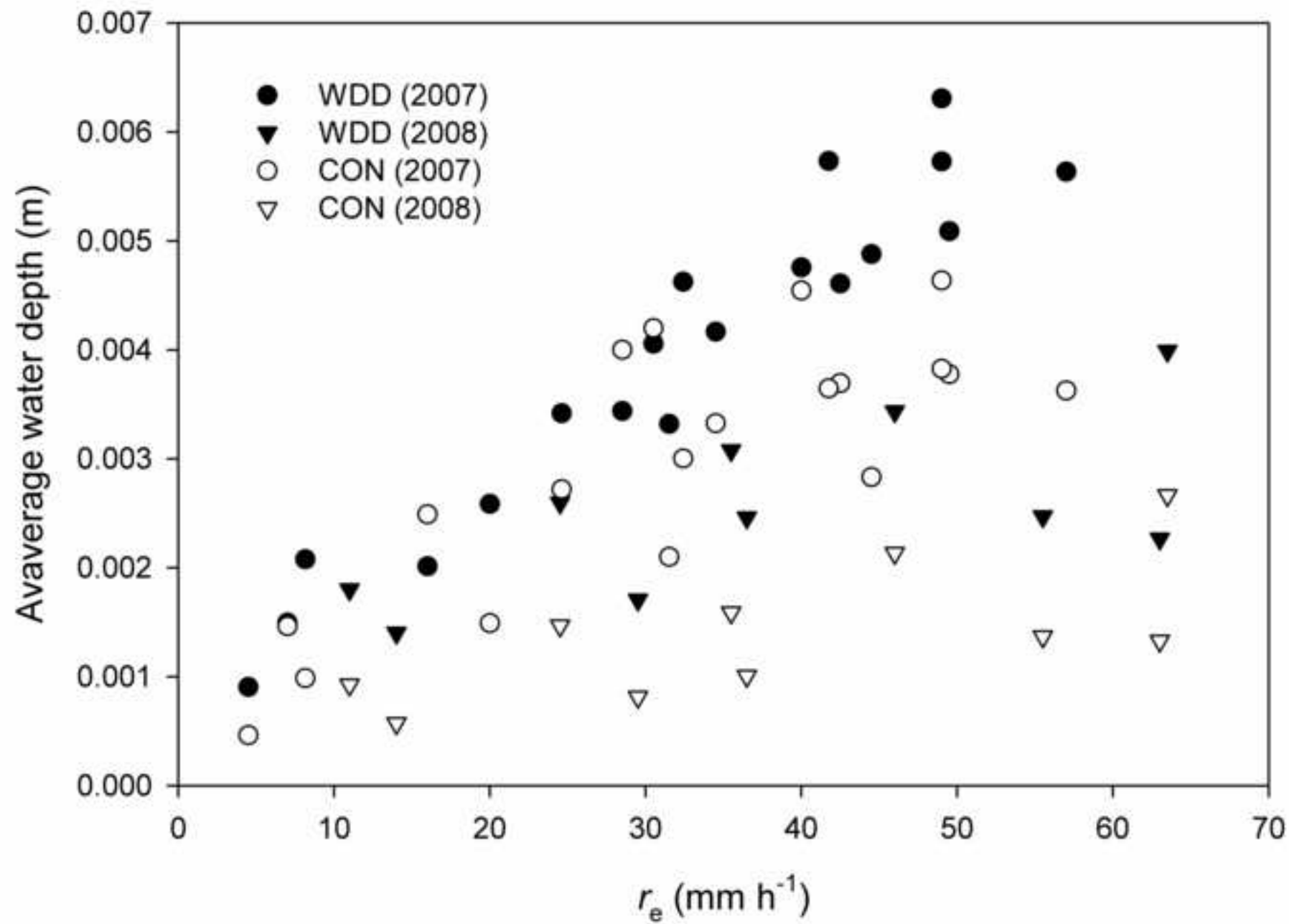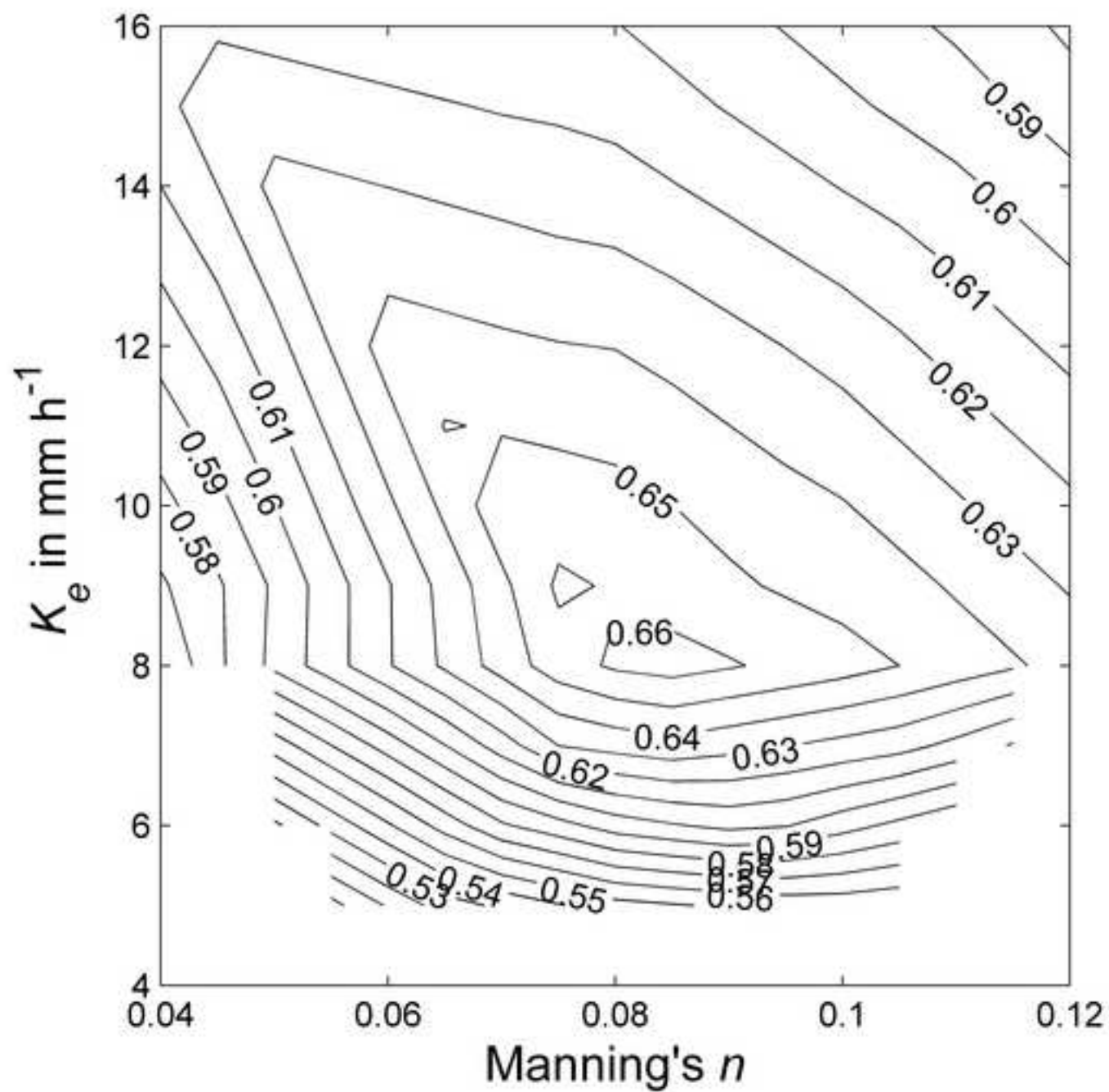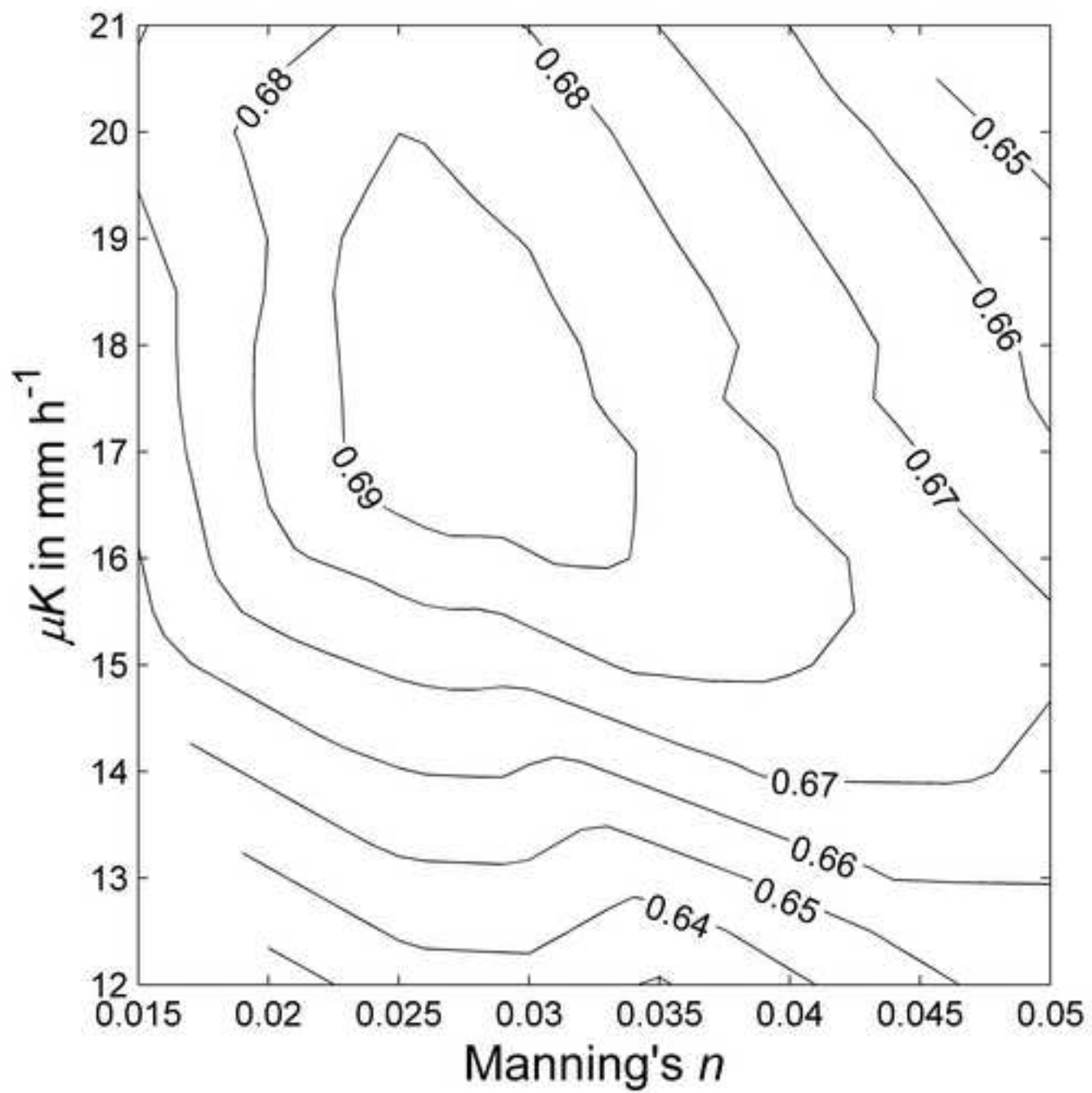899 stepped, solid line with an inverted scale on the right.

Figure1

Figure2

Legend:
- Approximate extent of Watershed LH-106
- Contour lines (0.2 m contour interval)
- **X** Location of H-flume

1368 m
1367 m
1366 m
1365 m
1364 m
1363 m

0 10 20 40

Meters

Figure3

Figure4

Creosote bush

A_c

Rainfall-limited infiltration

A_i

High conductivity

stones

D

Low conductivity

~ 0.2 m

~ 1.5 m

Rainfall-limited infiltration

(A_c)

A_i

Creosote bush

D

stones

High conductivity

Low conductivity

~ 0.2 m

~ 1.5 m

Figure6

Figure7

Figure 8

Figure 9a

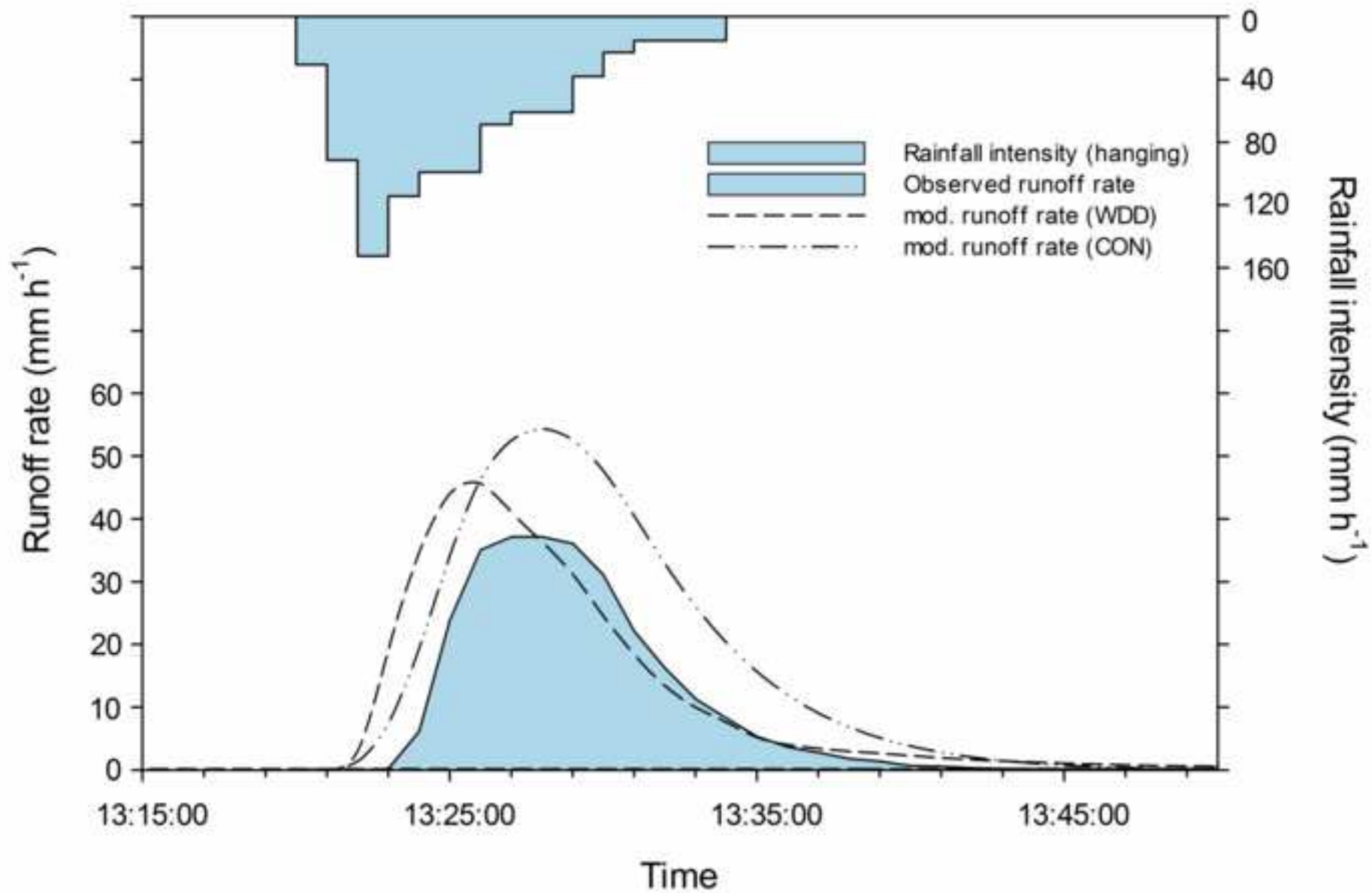**Figure 9b**

Figure 9c

Figure 9d

Figure 10
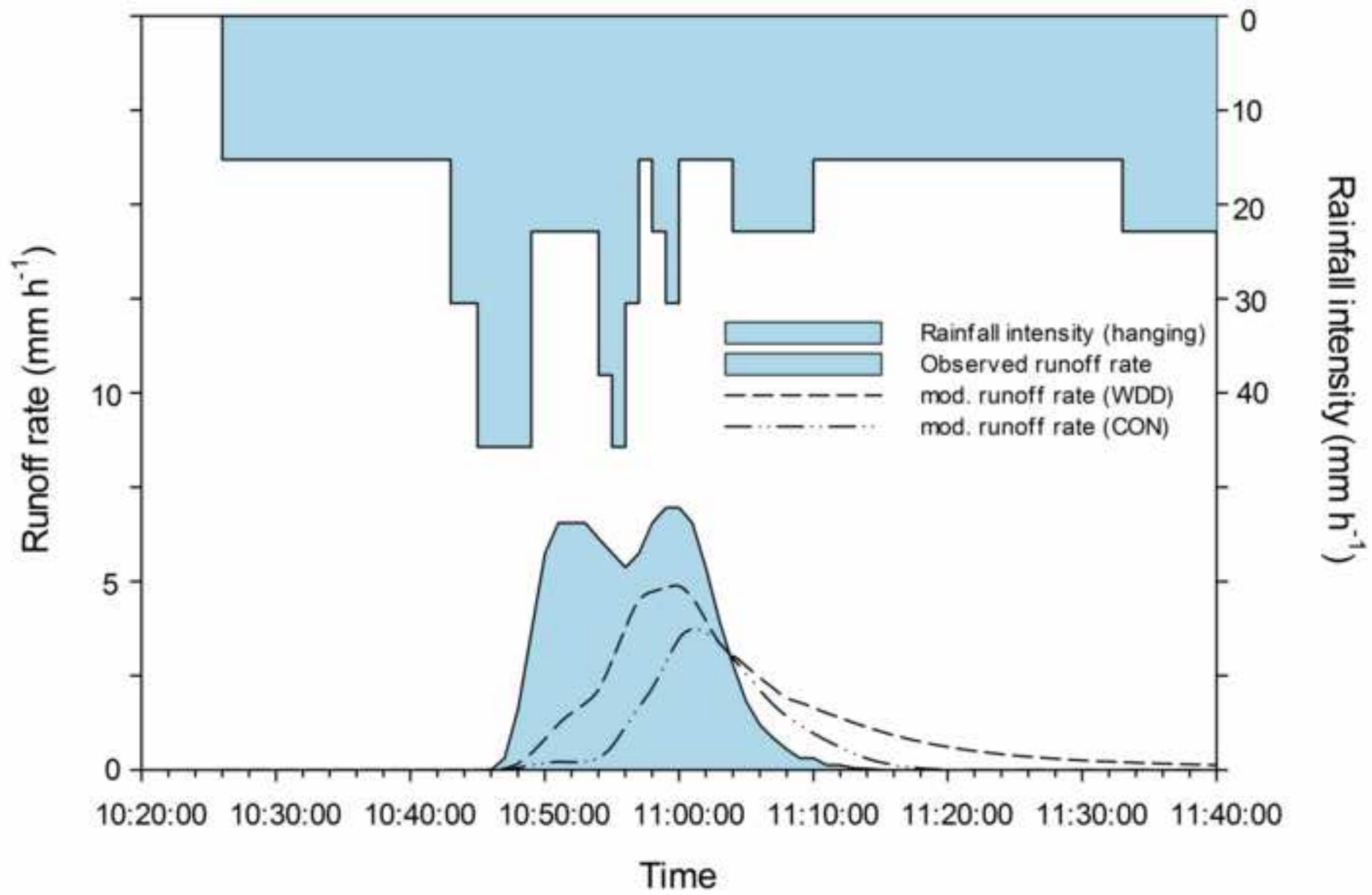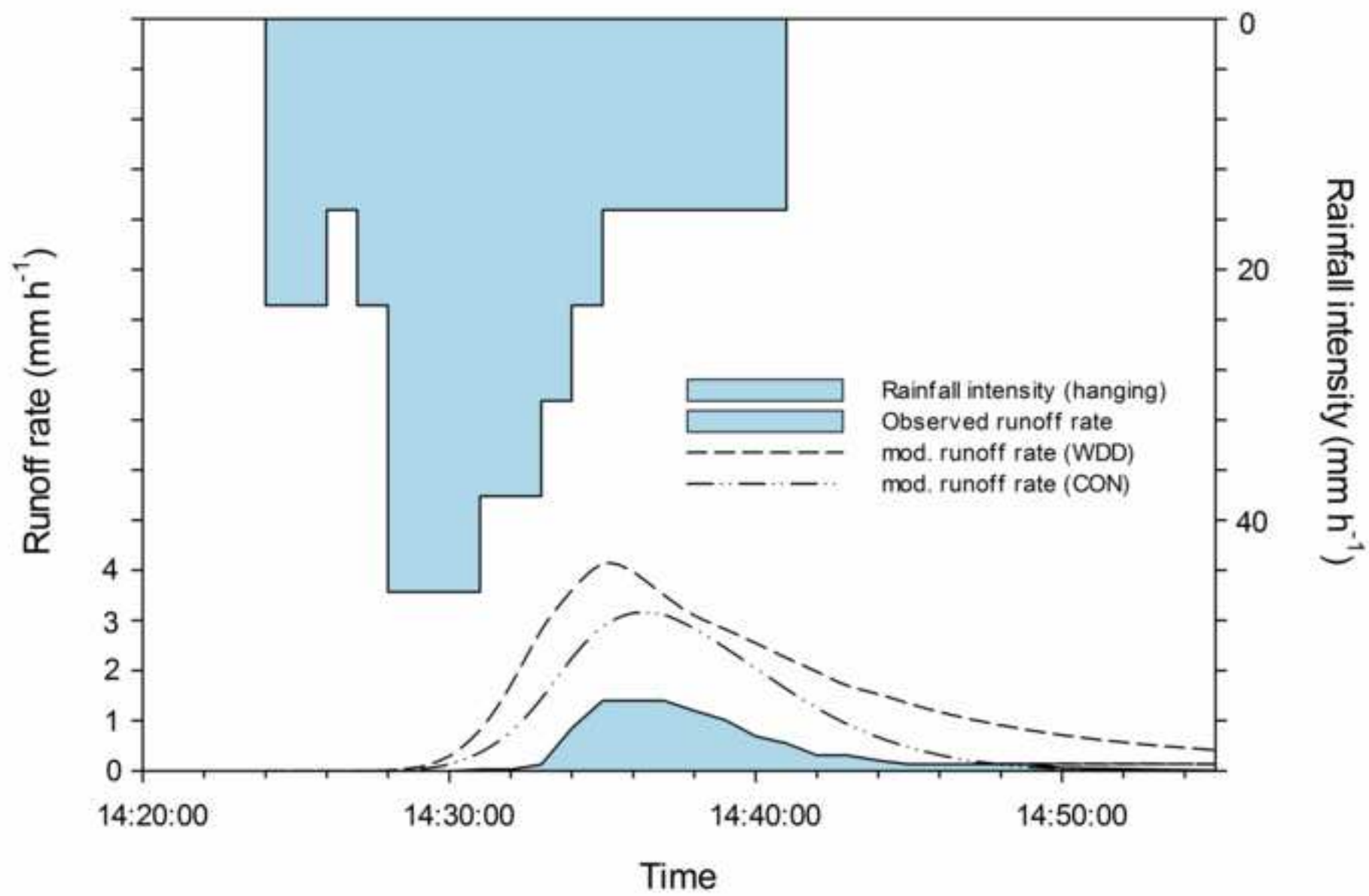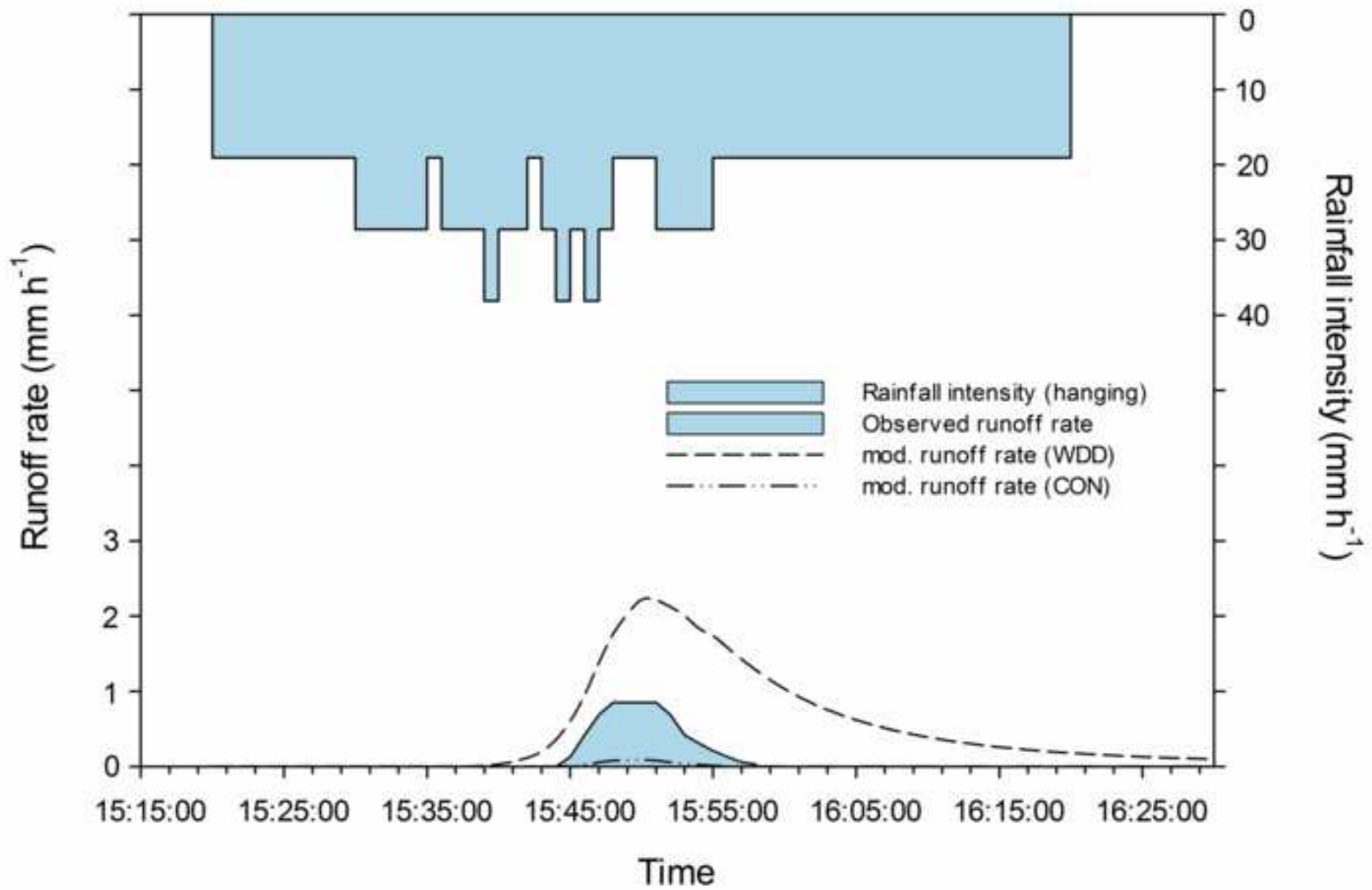
Figure 10

Table 1: Basic statistics of the rainfall simulation and rainfall events data set[a]

	Rainfall simulations[c]			Rainfall events					
	Cal. LP	Val. LP	Val. SP	P (mm)	Q_t[d] (m³)	Q_e[d] (mm h⁻¹)	Q_p[d] (mm h⁻¹)	Max. i (mm h⁻¹)	θ_i (-)
Number[b]	29 (5)	23 (4)	13 (3)	147	58	58	58	147	147
Mean	125.5	102.7	127.3	11.6	19.0	14.5	25.7	45.0	0.11
STDV	41.1	45.9	52.3	8.5	22.7	15.6	28.3	41.7	0.04
Min	61.5	25.4	46.7	4.6	0.4	0.51	0.69	1.9	0.03
Max	179.5	177.8	216.2	46.4	91.1	55.2	108.6	175.3	0.21

[a]LP: large plots (6 x 2 m), SP: small plots (1.22 x 0.61 m); P: total precipitation of an event; Max i: maximum one minute interval rainfall intensity; θ_i: pre-storm (initial) volumetric water content of soil. [b] Value in brackets is number of plots. [c] Statistics refer to applied rainfall intensity (mm h⁻¹). [d]Q_t: total runoff, Q_e, effective discharge, Q_p: peak discharge; statistics apply to runoff producing events only.

Table 2: Optimized parameter values calibrated for the watershed scale from runoff hydrographs for both models (CON and WDD), with and without runon infiltration, and parameters optimized for steady state rainfall simulation plot infiltration ('Plot')

	CON		WDD		Plot	
	With runon infiltration	Without runon infiltration	With runon infiltration	Without runon infiltration	CON	WDD
Ψ (mm)	31	22	139	175	-	-
μK (mm h^{-1})	-	-	16.5	14.5	-	62.4
K_e (mm h^{-1})	8	14	-	-	57.2	-
Manning's n	0.085	0.05	0.028	0.026	0.27	0.57

Table 3: Fraction of modelled events with a Nash-Sutcliffe Model Efficiency (ME) in a given class, coefficients of determination (R²) for measured vs. modeled Q_t, Q_e and Q_p for all rainfall events, and objective measure (OBJ, Equation 21). Parameters were optimized to maximize OBJ, given the CAL dataset and validated with the VAL dataset (Table 1). Both models were calibrated with and without runon infiltration.

		CON With runon		CON Without runon		WDD With runon		WDD Without runon	
		CAL	VAL	CAL	VAL	CAL	VAL	CAL	VAL
ME	> 0.75	0.37	0.11	0.37	0.21	0.37	0.32	0.37	0.29
	0.75> x > 0.5	0.1	0.14	0.07	0.11	0.23	0.15	0.23	0.18
	0.5 > x > 0	0.13	0.21	0.16	0.18	0.07	0.07	0.07	0.07
	< 0	0.4	0.54	0.4	0.5	0.33	0.46	0.33	0.46
R²	Q_t	0.82	0.62	0.88	0.76	0.94	0.86	0.94	0.85
	Q_p	0.91	0.67	0.94	0.69	0.89	0.72	0.89	0.72
	Q_e	0.93	0.78	0.94	0.74	0.93	0.79	0.93	0.79
OBJ		0.66	0.48	0.66	0.55	0.70	0.59	0.70	0.59

Highlights

- Development of new infiltration model based on Green and Ampt
- Combining water depth-dependent infiltration and partial contributing area concepts
- Good runoff predictions at rainfall simulator and small catchment scales
- Runon infiltration on hillslopes is an important process in semi-arid environments