Pasture BMP Effectiveness Using an HRU-based Subarea Approach in SWAT

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Abstract

Many conservation programs have been established to motivate producers to adopt best management practices (BMP) to minimize pasture runoff and nutrient loads, but a process is needed to assess BMP effectiveness to help target implementation efforts. A study was conducted to develop and demonstrate a method to evaluate water-quality impacts and the effectiveness of two widely used BMPs on a livestock pasture: off-stream watering site and stream fencing. The Soil and Water Assessment Tool (SWAT) model was built for the Pottawatomie Creek Watershed in eastern Kansas, independently calibrated at the watershed outlet for streamflow and at a pasture site for nutrients and sediment runoff, and also employed to simulate pollutant loads in a synthetic pasture. The pasture was divided into several subareas including stream, riparian zone, and two grazing zones. Five scenarios applied to both a synthetic pasture and a whole watershed were simulated to assess various combinations of widely used pasture BMPs: (1) baseline conditions with an open stream access, (2) an off-stream watering site installed in individual subareas in the pasture, and (3) stream or riparian zone fencing with an off-stream watering site. Results indicated that pollutant loads increase with increasing stocking rates whereas off-stream watering site and/or stream fencing reduce time cattle spend in the stream and nutrient loads. These two BMPs lowered organic P and N loads by more than 59%, and nitrate loads by 19%, but TSS and sediment-attached P loads remained practically unchanged. An effectiveness index (EI) quantified impacts from the various combinations of off-stream watering sites and fencing in all scenarios. Stream bank contribution to pollutant loads was not accounted in the methodology due to limitations of the SWAT model, but can be incorporated in the approach if an amount of bank soil loss is known for various stocking rates. The proposed methodology provides an adaptable framework for pasture BMP assessment and was utilized to represent a consistent, defensible process to quantify the effectiveness of BMP proposals in a BMP auction in eastern Kansas.

Keywords: Best Management Practices; Grazing management; Hydrologic Response Unit; Pasture; Livestock; SWAT

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1. **Introduction**

Over 191 million hectares, or more than 50% of pastureland, rangeland, and woodland in the United States, are used for livestock grazing activities (USDA-NASS, 2008). These activities may contribute to impairment of water bodies by polluting nutrients, bacteria, and sediment (Haan *et al*., 2006; U.S. EPA, 2004). Use of rivers and streams as a primary source of water for livestock leads to increased grazing time in or near the stream, resulting in direct deposition of animal waste into the stream accompanied by bank erosion at stream access and crossing locations. Properly implemented best management practices (BMP) can significantly reduce the pollutant footprint of grazing lands. One goal for grazing management and sediment-control BMPs is to protect sensitive areas of the pasture, such as streams, riparian zones, and ponds, by restricting livestock access.

Common BMPs that support stream protection consist of an alternative off-stream water source, a riparian buffer, and exclusion fencing (U.S. EPA, 2004). The alternative water source attracts livestock away from primary water bodies, such as streams, ponds and lakes, whereas the fencing completely eliminates access to streams and prevents direct animal waste contribution as well as mechanical disturbance to banks that may cause excessive soil erosion. Fencing requires that an alternative off-stream water source exists. Riparian areas along a stream function similar to vegetative filters at the edge of agricultural fields by filtering runoff and trapping pollutants before they reach the stream (Mankin et al., 2007).

Many studies (Sheffield et al., 1997; Line et al., 2000; Agouridis et al., 2005) observed substantial decrease in sediment losses after stream fencing. For example, Owens et al. (1996) observed that after stream and riparian buffer were fenced, annual TSS concentrations decreased by 50% over the following five years. Line et al. (2000) and Sheffield et al. (1997) reported TSS concentration reductions of more than 80%. In these studies, concentrations of total nitrogen (N) and phosphorous (P) were also reduced by 50% to 70%. In all reported cases, reductions in pollutant loads were caused by improvement to stream banks and reduction in the associated bank erosion due to reduction in bank disturbance by cattle. The

56   mineralized components of N and P loads are attached to and transported with sediment; therefore, N and

57   P reductions correlate with reductions in sediment concentrations.

58   A few field studies were conducted to assess stream water-quality improvement due to restriction of

59   stream access for cattle on grazing fields (Miner et al., 1992; Owens et al., 1996; Sheffield et al., 1997;

60   Line et al., 2000; Agouridis et al., 2005). Miner et al. (1992) and Sheffield et al. (1997) observed above

61   90% reduction of time cattle spent in stream if the off-stream watering site was introduced. Clawson

62   (1993) reported 81% time reduction and concluded that cattle preferred to drink 75% of the time from

63   trough than from stream. McInnis and McIver (2001) found small reductions in near-stream hoof traffic

64   from off-stream water and salt, but these reductions yielded significant reductions in development of

65   unstable stream banks. Daily use of a stream with no off-site water source in the pasture varied from

66   relatively short periods (4.7 min. by Clawson, 1993; 6.7 min. by Sheffield et al., 1997; and 14.5 min. by

67   Miner et al., 1992) to prolonged periods of above 90 min. (Pandey et al., 2009). Such variation in daily

68   stream use leads to differences in water-quality impact and improvements if the stream is fenced or

69   restricted. Agouridis et al. (2005) monitored cattle spatial variability within two pasture fields, and

70   statistically analyzed cattle positions over a 1.5-year period, and concluded a positive correlation between

71   the stream bank erosion and stocking density at 50 stream cross-sectional areas.

72   Preferential grazing patterns within a pasture cause concentrated points of manure depositions, which

73   affect native levels of soil organic nutrient components. Spatial variation of soil properties also can be due

74   to geological factors or can be imposed by soil management practices. Sauer and Meek (2003) studied

75   spatial variation of soil P in two pasture fields. The impact of morphological factors was found to be

76   secondary to management factors. They also found that the history of grazing activity in the pasture

77   affects nutrient content in soil, thus affecting pollutant runoff. Areas of higher P occur mostly near gates,

78   roads, stream, and watering sites (Sauer and Meek, 2003; Penn et al., 2009). Areas of high slope have

79   greater potential to generate surface runoff, accompanying soil loss, and sediment-attached P than areas

80   with low slope (Haan et al., 2006). Representation of these preferential grazing patterns and

81   morphological features are needed in models to better assess the environmental impact of grazing BMPs.

82   Phosphorous loss in runoff is considered an important indicator of pasture environmental quality, and

83   several models were developed to assess impacts of grazing BMPs on soil health (USDA-NRCS, 1994;

84   Wade et al., 1998; White et al., 2009; Nelson and Shober, 2012). The Phosphorous Index (PI) model is a

85   qualitative tool to assess various land forms for potential risk of P runoff to water bodies (USDA-NRCS,

86   1994; Nelson and Shober, 2012). The tool computes P index rating for a pasture area as a sum of eight P

87   loss factors and weighting coefficients. P loss factors range from low to high and split into categories

88   related to soil erosion, runoff , soil test P, P fertilizer application rate and method, and organic P source

89   application rate and method (Lemunyon and Gilbert, 1993). The P index rating result from application of

90   weighted coefficients to interpret the site vulnerability ratings. The tool mainly relies on general pasture

91   information and does not use spatial characteristics or management operations. The Grazing Potential

92   Index model (GPI; Wade et al., 1998) uses land characteristics, pasture proximity to the stream, and

93   forage availability to assess environmental potential. The model statistically distributes cattle within the

94   pasture based on geographical features such as the nearest permanent water source(s), land slopes, and

95   forage availability, and assigns a GPI score to different areas within the watershed. The areas with higher

96   GPI scores are expected to be favored by livestock. Although this model produces spatial representations

97   of grazing patterns, it does not quantitatively calculate nutrient loads to the stream. The Pasture

98   Phosphorous Management (PPM) calculator (White et al., 2009) is a quantitative P assessment tool that

99   uses the Soil and Water Assessment Tool (SWAT) model to pre-process P loads for individual

100   Hydrologic Response Units (HRU) and lets a user select the corresponding representation of the grazing

101   area. Grazing management operations, stocking rates, and fertilizer applications are inputs to the model

102   on a monthly basis. The PPM Calculator presents a quantitative way to evaluate the P runoff from a

103   pasture; however, it does not account for unique land characteristics at different parts of the pasture,

104   grazing spatial patterns, and direct stream contribution.

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105   To minimize pasture runoff and nutrient loads, many conservation programs, traditional cost-share

106   programs, or cost-effective alternative programs have been established to motivate producers to adopt

107   BMPs (Smith et al., 2007; Smith et al., 2009). Administration of these programs would benefit from a

108   better understanding of the site-specific pollutant-load reductions associated with the proposed BMPs in

109   order to better evaluate the environmental benefits associated with program costs. The three presented

110   above models cannot be directly used to quantify site-specific environmental impacts of pasture BMPs,

111   which would be beneficial for accurate assessment of field condition. Therefore, the objective of this

112   study was to develop and demonstrate a new method of utilizing site-specific pasture characteristics and

113   cattle grazing patterns for determining average annual pollutant load and calculating an index of pasture

114   BMP effectiveness. Demonstration and application of this method to pastures in Pottawatomie Creek

115   watershed in eastern Kansas and a single synthetic pasture will be discussed.

2. Methods and Materials

2.1. Pasture design

118   Pasture fields are lands of low-growing vegetation (grasses, shrubs, plants, etc.) utilized for animal

119   grazing. Pasture fields differ in size, topography, soil characteristics, forage type, and grazing

120   management and normally contain an access point to water. A typical water source can be a stream

121   flowing through pasture or an alternative off-stream watering site (a pond or an artificially build trough)

122   (Ohlenbusch and Harner, 2003). A pond or any alternative source of water that is hydrologically

123   disconnected from a stream provides an opportunity to capture majority of animal waste that otherwise

124   would have been excreted directly into the stream. A vegetative buffer or riparian area is a native or

125   created buffer adjacent to a stream to reduce pollutant transport to the streams (U.S. EPA, 2004).

126   In this study, we defined a pasture to consist of three parts: a grazing area, a riparian area, and a stream.

127   The grazing area represents a main area for cattle to graze. The riparian area can be a buffer zone along

128   the stream or forested inclusions within the grazing area. The stream area is defined as area that envelops

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129 the stream and by its land cover characteristics cannot be interpreted as riparian buffer. If an alternative

130 watering site is present, it is assumed to be located within the grazing area and have no direct outflow to

131 the stream. Both the grazing area and the riparian buffer can be divided further into subareas according to

132 individual land characteristics, such as topography, soil type, and land cover, and management operations.

133 Within each subarea, the characteristics are assumed to be uniform.

2.2. Stocking rate

135 Variability in grazing distribution can be accounted by using individual stocking rates (*SR*) for each

136 subarea. Generally, the average SR for an entire pasture area is expressed as the number of animal units

137 (AU; $1\ AU = 1{,}000$ kg of animal weight) allocated per unit of land area *A* (1 ha) in one day (Ohlenbusch

138 and Watson, 1994; Redfearn and Bidwell, 1997). For an individual subarea *i* in the pasture, the local

139 stocking rate (SR_i) relates to a daily fraction of the grazing time by:

$$SR_i = [\text{Number of } AU][\%\text{Time}]/A_i \tag{1}$$

141 while average stocking rate SR_{AVG} for pasture with *N* subareas can be expressed using an area-weighted

142 approach as

$$SR_{\text{AVG}} = \sum_{i=1}^{N}(SR_i A_i)/\sum_{i=1}^{N} A_i \tag{2}$$

2.3. SWAT model

145 The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2004, 2005) is a

146 widely used watershed model (Gassman et al., 2007; Douglas-Mankin et al., 2010) that was utilized in

147 this study to simulate hydrological and water-quality processes at the field (or pasture) and watershed

148 scales. SWAT is a complex continuous simulation model that incorporates a set of both physically and

149 empirically based equations within multiple modules that proceed either independently of each other or

150 use outputs of one module as inputs for another module within one time-step. Both pasture-scale and

151 watershed-scale modules are implemented in SWAT. Based on topography and using the Geographic

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152 Information System (GIS) module within ArcGIS (ESRI, 2011) for pre-processing geospatial layers,

153 SWAT delineates a watershed into subwatersheds that are further subdivided into areas of homogeneous

154 soil type, land cover, and slope range, called Hydrologic Response Units (HRU). HRUs are used to

155 simulate all processes that occur at the pasture scale, including hydrologic budget, plant growth, erosion,

156 and nutrient cycles. The amount of water, nutrients, and sediment flowing from the HRUs into streams

157 are accounted at the daily time scale and collected as HRU outputs.

158 Applying the HRU framework to pasture area, subareas within the pasture can be represented by

159 individual HRUs. For example, pasture (identified in SWAT as PAST) and rangeland (RNGE) land cover

160 represent grazing subareas, and deciduous forest (FRSD) and range-brush mix (RNGB) represent riparian

161 subareas. We note that stream subarea was not simulated in SWAT.

162 SWAT requires a large number of input parameters that are divided into the groups of watershed-scale

163 and pasture-scale parameters. Many watershed-scale parameters, such as land cover, soil, geographical

164 features, and groundwater parameters, are either loaded directly as attributes of geospatial layers or

165 calculated from them. Twelve pasture-scale parameters that relate to land management and practices in

166 the pasture are presented in Table 1 and applied to grazing and riparian HRUs. The amount of minimum

167 dry above ground biomass at which grazing is permitted, pasture initial conditions, operation schedule,

168 and daily amounts of biomass consumed and trampled are input into the SWAT project database based on

169 the SR and knowledge of animal behavior in the pasture.

170 Loadings of six specified pollutants (soluble P [defined in SWAT by SOLP], organic P [ORGP],

171 sediment-attached P [SEDP], organic N [ORGN], nitrate [NO_3-N], and suspended solids [TSS]) for each

172 subarea in the pasture besides the stream subarea are collected from the unit-area HRU outputs (ω). For

173 stream subareas an approach is used based on fractions of nutrients in animal waste that are directly

174 applied to the stream load:

$$\omega_{\text{stream}} = \chi \cdot m \cdot SR_{\text{stream}} \qquad (3)$$

176 where $m=8.5$ kg, and χ is percent of the selected nutrient constituent in dry solid manure, 1.0% for NO_3-

177 N, 3.0% for ORGN, 0.4% for SOLP, 0.7% for ORGP, and 0% for SEDP and TSS according to the ASAE

178 standards (ASAE, 1999) and SWAT database (Neitsh et al., 2005). Total load W_{pasture} of each pollutant for

179 the entire pasture can be calculated as:

$$W_{\text{pasture}} = \omega_{\text{stream}} A_{\text{stream}} + \omega_2 A_2 + \omega_3 A_3 + \cdots + \omega_N A_N \qquad (4)$$

2.4. BMP effectiveness

182 Various pasture BMPs are designed to improve water-quality conditions in the pasture; reduce P, N,

183 and TSS loads; and optimize grazing management. Among many pasture BMPs such as cross fencing,

184 stream fencing, rotational grazing, and alternative watering sites, only a few can be represented within

185 current continuous water-quality models. In this study, a procedure was developed to simulate two pasture

186 BMPs, both related to reducing stream access: creating off-stream watering sites and fencing streams

187 and/or buffers (Ohlenbusch and Harner, 2003). By establishing an off-stream watering site in upland

188 subareas of the pasture, it increases the fraction of daily time that cattle graze there, which increases SR in

189 the subarea of the alternative watering site and reduces SR in the area near the stream. If fencing is

190 applied, the fenced areas (stream or buffer) are considered inaccessible for grazing, and SR in these areas

191 is set to zero.

192 Two types of modeling scenarios were introduced in this study. Grazing scenario in a pasture with no

193 implemented BMPs will be called the baseline scenario, while a pasture with implemented fencing or off-

194 stream watering site will be called a BMP scenario. A water-quality impact of implemented BMPs can be

195 calculated by comparing the pollutant loads in baseline and BMP scenarios using either an effectiveness

196 index (EI, %) for a single pollutant or the cumulative effectiveness index (CEI, %) in the case of M

197 multiple pollutants:

$$EI_j = \frac{W_j^{baseline} - W_j^{BMP}}{W_j^{baseline}} 100\%, \qquad CEI = \sum_{j=1}^{M} \left(\phi_j EI_j \right) \qquad (5)$$

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199 where j represents a pollutant and ϕ_j are weighting coefficients according to pollutant ranking table. In this

200 study, the six pollutants ($M=6$) specified above as outputs of the SWAT model were considered of equal

201 importance, thus, ϕ_j =0.167.

3. Study area

3.1. Model setup

204   The pasture BMP effectiveness method was tested in the 897-km^2 Pottawatomie Creek Watershed in

205 eastern Kansas (Fig. 1). The SWAT ver. 2005 model was built for the watershed with the main outlet set

206 at the USGS gauging station 06914100 on Pottawatomie Creek near the town of Scipio, Kansas (USGS,

207 2009; Fig. 1b). Based on geospatial datasets of 10-m Digital Elevation Model, 30-m NLCD land cover,

208 and SSURGO soil database (Homer *et al*., 2007; USDA-NRCS, 2005; Sheshukov et al., 2011), the

209 watershed was delineated into seven subwatersheds and 6066 HRUs. Watershed land uses were primarily

210 grazing land (46%) and cropland (30%), and soil was predominantly (80%) silt loam of high runoff

211 potential (hydrologic soil group type D). According to land-ownership parcels in eastern Kansas, the

212 watershed is comprised of 403 sections of land (260 ha, 640 acres) with grazing land occupying on

213 average 163 ha (from 13 ha to 250 ha) of each section (Fig. 1b). Following practices used in eastern

214 Kansas, continuous corn with a mix of conventional and no-till practices were applied to all cropland

215 HRUs, while pasture HRUs had tall fescue grass growing all year and grazed with an average SR of 0.8

216 AU/ha.

217   Due to availability of edge-of-field sampling data, a 3.5 hectare dairy pasture field in subwatershed 7

218 composed of tall fescue grass in low slope (80%) and high slope (20%) areas was identified for pasture

219 scale analysis. Three HRUs represented the pasture and 200 dairy cattle were grazed throughout the year.

220 Specific grazing management operation parameters used in the model are provided in Table 1.

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221   Timeseries of daily temperature and precipitation from 1995 to 2005 from two NCDC cooperative

222   weather stations 143008 and 143441 (NCDC, 2009) were collected for weather input in subwatersheds 1

223   to 6. For subwatershed 7, daily records from the onsite weather station at the dairy pasture were used

224   instead. The model was run for seven years (1999-2005), with the first 2 years used for model spin-off.

3.2. Model calibration

226   Two types of calibration procedures were conducted to ensure acceptable performance of the SWAT

227   model at both the watershed and pasture scales. First, the simulated daily streamflow was compared with

228   data from the gaging station at the watershed outlet. The following statistical parameters were used for

229   calibration (Moriasi et al., 2007): the Nash-Sutcliffe efficiency coefficient (NSE; Nash and Sutcliffe,

230   1970), the coefficient of determination (R^2), the root mean square error to standard deviation ratio (RSR),

231   and the percent bias (PBIAS). Seven model parameters shown in Table 2 were adjusted during hydrologic

232   calibration process. The final statistics presented in Table 3 was rated from very good (NSE > 0.75; RSR

233   ≤ 0.50) to good ($\pm 10\% \leq$ PBIAS < $\pm 15\%$) according to Moriasi et al. (2007). Second, water samples from

234   2001 to 2005 were used to calibrate the model for sediment and nutrient runoff at the pasture scale

235   (Mankin et al., 2007; Fig. 1c). An automated sampler (Model 6700; Onset, 2008) was installed at the edge

236   of the pasture field, and a total of 22 flow-weighted water samples were collected on a bi-weekly schedule

237   from multi-day runoff events. Samples were analyzed for total phosphorous (P), nitrate (NO_3-N), and

238   suspended solids (TSS) using methods described in APHA (1998). The observed concentrations were

239   compared with the SWAT-simulated concentrations of the same pollutants aggregated for each sampling

240   period using area-weighted concentrations from three HRUs comprising the pasture field. Five model

241   parameters (Table 2) were adjusted during the calibration process, which resulted in satisfactory model

242   performance for TSS (PBIAS < $\pm 55\%$) and very good performance for total P and NO_3-N (PBIAS <

243    $\pm 25\%$) (Table 3; Moriasi et al., 2007). In addition, mean and ranges of observed and calibrated

244   streamflow and pollutant concentrations were compared in Table 3 and showed adequate model

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245 performance. Based on the statistics of two calibration procedures, the model was deemed acceptable for

246 simulation of pasture BMP effectiveness.

3.3. Synthetic pasture scenarios

248   After the SWAT model was built and calibrated at the watershed and pasture scales, an example

249 synthetic pasture was configured to evaluate effectiveness of pasture BMPs. The distribution of pasture

250 and forest HRUs and a stream length in the watershed were used as basis to design a synthetic pasture.

251 Based on total area of all pastureland as 51,300 ha, total length of streams crossing through pastureland as

252 789 km, and assuming typical 10-meter wide floodplain and 15-meter wide riparian zone on each side of

253 the stream, stream area and riparian buffer were found to occupy 1.6% and 4.5% of total pastureland in

254 the watershed, respectively. These percentages were used to define subareas within the synthetic pasture.

255 A synthetic pasture was selected to represent a quarter-section (65 ha, 160 acres) of land-ownership parcel

256 and contained an in-stream area (1 hectare; defined as S), a riparian zone (3 hectares; R), and grazing area

257 (61 hectares). To account for land variability, the grazing area was additionally divided into two grazing

258 subareas G1 and G2 of the same soil type.

259   An average slope of all pastureland was 1.2%, with riparian areas sloped at 0.4%. The subarea G1 was

260 selected to represent low slope topography, whereas G2 covered high-slope area. Areas of G1 and G2

261 varied for different scenarios and SWAT runs. Three specific HRUs from the SWAT model were selected

262 to represent pasture subareas; two HRUs identified with PAST landuse represented areas G1 and G2, and

263 one HRU with RNGE landuse represented area R. Two HRUs selected for G1 and R had slopes of 0.4%

264 for all runs. The slope of the second pasture HRU for G2 was appropriately adjusted to satisfy the average

265 pasture slope of 1.2%, and SWAT model was reran for each new scenario.

266   Cattle stocking rate of 0.8 AU/ha/day were used for uniform grazing within the whole synthetic pasture

267 without considering preferential grazing patterns. Daily amount of time that cattle spent in each subarea

268 was strictly based on the area of grazing and riparian subareas, while for not-fenced stream subarea it was

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269   assumed at 14 minutes (1% of each day). This selected duration of stream time was similar to Miner et al.

270   (1992), however, other durations of up to 140 minutes (10%) were also tested in simulations.

271   The baseline and four BMP scenarios were simulated for the synthetic pasture. In the baseline

272   scenario, cattle spent 14 minutes (1% of 24 hours) in stream subarea, 67 minutes in subarea B, and 1,359

273   minutes in subareas G1 and G2. The first two BMP scenarios, W1N and W2N, simulated BMPs with off-

274   stream watering site installed in grazing areas G1 and G2, respectively, and no stream fencing. Because of

275   the presence of off-site watering site, the stream time was assumed to be reduced by 90% as similar to

276   Miner et al. (1992) and Sheffield et al. (1997). Other reductions in stream time (from 50% to 100%) were

277   also tested and discussed in section 4. The final two BMP scenarios, W1F and W2F, represented a

278   combination of an off-stream watering site in either G1 or G2 complemented by stream fencing. In these

279   two scenarios cattle has no access to stream and spend all daily time grazing in subareas G1 and G2.

4. Results

281   The SWAT model for the Pottawatomie Creek watershed, calibrated at watershed and pasture scales,

282   was run many times with stocking rates varying from 0 to 3 AU/ha applied to all grazing (RNGE, HAY)

283   and forested (FRSD, RNGB) HRUs. For each run, annual average loads of six pollutants (TSS, SEDP,

284   ORGP, SOLP, ORGN, NO_3-N) were collected in all HRUs, aggregated to represent the pasture according

285   to Eq. (4), and used to calculate pasture BMP effectiveness indices EI and CEI with Eq. (5). The results

286   were applied to simulate baseline and four BMP scenarios for the following two pasture sets: (1) a single

287   synthetic pasture comprised of four subareas and (2) all 403 pastures in the entire Pottawatomie Creek

288   watershed. Synthetic pasture scenarios and results are presented in details while the statistics of the BMP

289   applications to the entire watershed is summarized and discussed.

290   Annual average loads for the synthetic pasture are presented in Fig. 2a for the baseline scenario, while

291   the loads for four BMP scenarios are shown in Fig. 2b as changes from the baseline. The subareas G1,

292   G2, R, and S were set as default at 50 ha, 11 ha, 3 ha and 1 ha, respectively. In addition, range bars in Fig.

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293   2a represent ranges of loads for grazing subarea G1 varying from 0 to 61 ha. Pasture pollutants related to

294   sediment runoff show the largest variation in loads with the change in area of G1, with the loads of TSS

295   and SEDP increasing 14 times from pasture configuration with 100% G1 and no G2 area to the

296   configuration with no G1 and 100% G2 area (Fig. 2a). The high-slope subarea G2 produces 20 times

297   more sediment runoff than G1, thus contributing more to TSS and SEDP loads with a decrease of G1.

298   Loads of other pollutants (ORGP, SOLP, ORGN, NO_3-N) increased only by about 5% with decrease of

299   G1 indicating that they rely more on either phosphorous and nitrogen concentrations stored in the soil or

300   applied in a form of manure to the soil or directly in the stream. For the default case of G1 area of 50 ha,

301   the stream contribution to total pasture loads was 66% for ORGP, 94% for ORGN, and 21% for NO_3-N.

302   For SOLP, the major contributor was the grazing subarea G1 at 81%. The conducted additional tests with

303   different sizes of the riparian subarea revealed the decrease of total pasture TSS and SEDP loads with an

304   increase of riparian buffer.

305   Benefits of the reduction in stream time were apparent when examining net nutrient loads from BMP

306   scenarios when compared to their respective baseline scenarios (Fig. 2b). The reduction in stream time for

307   scenarios W1N and W2N relative to the baseline scenario reduced the pollutant stream contribution by

308   90% and reduced organic nutrient loads by 85% for ORGN, 59% for ORGP, and 19% for NO_3-N,

309   whereas SOLP, TSS, and SEDP loads remained practically unaffected. Fencing a stream in scenarios

310   W1F and W2F completely eliminated access to stream, thus increased stocking rates and manure

311   deposition in grazing subareas. However, the fencing led to only an incremental decrease in pollutant

312   loads in contrast with a substantial reduction caused by the off-stream watering site.

313   The impact of pasture topography on BMP effectiveness is presented in Fig. 3 for four BMP scenarios

314   by varying the area of G1 from 0% to 100% (61 ha) coverage. The CEI increased with the increase of G1

315   area for all BMPs reaching its maximum value when G1 area occupies 100% of the grazing land. Similar

316   to the analysis of pollutant loads presented in Fig. 2, the presence of off-stream watering site in scenarios

317   W1N and W2N had a much stronger impact on BMP effectiveness (CEI ranged from 19.7% to 31%) and

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318 pollutant load reductions than impacts caused by additional stream fencing. Two fencing scenarios (W1F,

319 W2F) consistently produced higher CEIs than a non-fencing scenario (W1N, W2N) for any percentage of

320 G1 area, however, the difference in CEI was only 1.8% for zero G1 subarea, and increased to 3.4% for G1

321 subarea occupying 100%. A placement of the watering site in a low-slope area G1 was slightly more

322 efficient than placing it in the high-slope area G2, with CEI increasing with the increase of contribution of

323 G1 in grazing area. This was also confirmed by assessing BMPs in all pastures in the watershed; average

324 CEI reduced from 38% for low-slope (0.01%) pasture to 31% for high-slope (6%) pasture.

325   Major factors influencing load calculations were the daily grazing times in pasture subareas, especially

326 in the stream. The stream time was assumed in the synthetic pasture configuration as 1% of daily time or

327 14 minutes for the baseline scenario; it was additionally reduced by 90% (1.4 minutes) for scenarios W1N

328 and W2N with off-stream watering site, or completely eliminated (0 minutes) for scenarios W1F and

329 W2F with stream fencing. The pre-BMP baseline stream time and its reduction as a result of BMP

330 scenarios can be considered site specific and may vary seasonally. The sensitivity of BMP efficiency to

331 the variability in stream time was evaluated in Fig. 4 by plotting CEI as a function of the reduction in

332 stream grazing time in W1N scenario. The daily stream grazing time varied from 7 minutes (curve 1) to

333 120 minutes (curve 4) for synthetic pasture scenarios. The CEI gradually increased as the stream time

334 increased, which reflects the fact that overall pollutant reduction was responsive to implementation of the

335 off-stream watering site. However, there were diminishing returns for each increment of stream time

336 increase; the relative magnitude of reductions decreased as stream time increased. In addition, CEI

337 increased for greater reductions in stream time for any given pre-BMP stream grazing time. A 100%

338 reduction in time represents the case of completely halting the stream access for grazing, which is similar

339 to stream fencing in W1F scenario. The increase in CEI that results from greater reductions in stream

340 time confirms intuition. However, also evident in Fig. 4 is that the rate of increase in CEI per unit of

341 reduction in time increases slightly as pre-BMP stream time increases. For example, a shift from 50% to

342 100% stream time reduction led to a 13% CEI increase for curve 1 (7 min) compared to a 18% CEI

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343 increase for curve 3 (30 min). Thus, settings in which cattle initially (pre-BMP) spend more time in the

344 stream may show a greater response per unit of reduction in stream time resulting from a given BMP.

345 Similar behavior was observed while evaluating all 403 pastures in the watershed. The range of CEI for

346 W1N scenario with 14-minute stream time is presented in Fig. 4 as a shaded area, while the mean trend is

347 shown by the dashed line. Comparing with curve 2 for the synthetic pasture, the watershed overall

348 exhibited better response and from 5 to 10% higher BMP effectiveness to off-stream watering site

349 installation.

5. Discussion

351 Studying the baseline scenario revealed that accounting for stream subarea in configuring a pasture can

352 increase nutrient contribution from pasture and substantially improve estimation of BMP efficiency.

353 Localized high-slope grazing areas in a pasture may affect hillslope hydrology, increase soil erosion and

354 transported pollutants.

355 The results presented in section 4 demonstrated that an off-stream watering site can positively affect

356 concentrations of animal waste in the stream by attracting livestock to spend longer times away from the

357 stream. Stream fencing provided additional reduction in pollutant loads; although, the increase in

358 effectiveness was marginal compared to the impact of an off-stream watering site. These results

359 correspond with the findings of Sheffield et al. (1997), Line et al. (2000), and Agouridis et al. (2005). For

360 $SR_{AVE} = 0.8$ AU/ha, keeping livestock away from the stream reduced organic components of P and N by

361 85% and 59%, nitrates by 19%, however, TSS and SEDP remained almost unchanged which contradicted

362 the other experimental studies (Sheffield et al., 1997). The disparity between the results mainly occurred

363 due to not accounting for stream bank erosion in SWAT, a potentially significant contributor to stream

364 TSS. A reduction in grazing time near a stream should decrease trampling and other deteriorating effects

365 on banks that were found important by Sheffield et al. (1997) and Aguoridis et al. (2005) but not

366 explicitly included in the SWAT model. We predict that accounting for bank erosion by incorporating

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367   stream bank soil loss components in Eq. (4) would increase the BMP effectiveness of both fencing and

368   off-stream watering site practices. Regardless of this shortcoming, the methodology presented in this

369   paper provides a viable tool to assist expert management teams in evaluating the effectiveness of an off-

370   stream watering site and stream fencing. As an example, this approach was used in making management

371   decisions to award producers for BMP implementation on producer pasture fields as part of the livestock

372   BMP auction (U.S. EPA, 2009). The awarded installation of the off-stream watering site not only

373   produced high effectiveness index but also appeared to be the most cost-efficient compared to other BMP

374   proposals. In contrast, the stream fencing and riparian buffer fencing was associated with higher cost and,

375   in the end, turned out to be less cost-efficient.

6. Conclusions

377   In this study, a modeling approach of pasture BMP effectiveness was developed based on HRU-based

378   representation of individual pasture subareas including stream, riparian zone, and various slope grazing

379   lands. Based on the HRU distribution in the SWAT model built for Pottawatomie Creek Watershed in

380   eastern Kansas , four scenarios with combinations of off-stream watering site and stream fencing BMPs

381   were evaluated in synthetic pasture and a whole watershed.

382   The presence of the off-stream watering site reduced the time cattle spent in the flood plain area as

383   well as the overall pollutant load in the stream. This resulted in the cumulative effectiveness index being

384   above 20% for all BMP scenarios, with an additional gain of 2% if the stream was fenced. Sediment

385   contribution from stream bank erosion was not accounted in the methodology due to limitations of the

386   SWAT model, but can be incorporated in the approach if an amount of bank soil loss is known for various

387   stocking rates. The methodology was applied to evaluate BMP proposals in a BMP auction conducted in

388   an eastern Kansas watershed.

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Figure Captions:

501

502   Fig. 1. Study watershed, showing (a) Pottawatomie Creek Watershed in east-central Kansas; (b) stream

503   network, delineated subwatersheds, grazing area in 260-hectare land parcels, weather stations, and USGS

504   gauging station used in streamflow calibration; and (c) aerial image of the Nichols dairy pasture used in

505   sediment and nutrient calibration.

506   Fig. 2. (a) Annual average loads of total suspended solids (TSS), organic P (ORGP), sediment-attached

507   P (SEDP), soluble P (SOLP), organic N (ORGN), and nitrates (NO3-N) for baseline scenario of the

508   synthetic pasture, and (b) load changes from the baseline for four BMP scenarios. Subareas G1, G2, R, S

509   were set as default at 50 ha, 11 ha, 3 ha, and 1 ha, respectively, while range bars in (a) represent grazing

510   subarea G1 varying from 0 to 61 ha.

511   Fig. 3. Pasture BMP cumulative effectiveness index (CEI, %) for four BMP scenarios as a function of

512   the percentage of subarea G1 in total grazing area.

513   Fig. 4. BMP cumulative effectiveness index (CEI, %) for W1N scenario in Pottawatomie Creek

514   watershed and synthetic pasture. The CEI is calculated for various daily stream grazing times as a

515   function of stream time reduction (based on increasing use of an alternative watering site). The shaded

516   area and dashed line illustrate range and a mean of CEI for 403 pastures in Pottawatomie Creek

517   watershed, while solid lines show CEI for synthetic pasture.

518

519 **Table Captions:**

520   Table 1. SWAT management operation input parameters and their values within a grazing land (G1,

521 G2) HRU and a riparian buffer (R) HRU (VAR means variable values).

522   Table 2. SWAT parameters adjusted during calibration runs in Pottawatomie Creek watershed.

523   Table 3. Observed streamflow, pollutant concentrations, and statistics for default and final calibration

524 runs in Pottawatomie Creek watershed (n is the number of samples).

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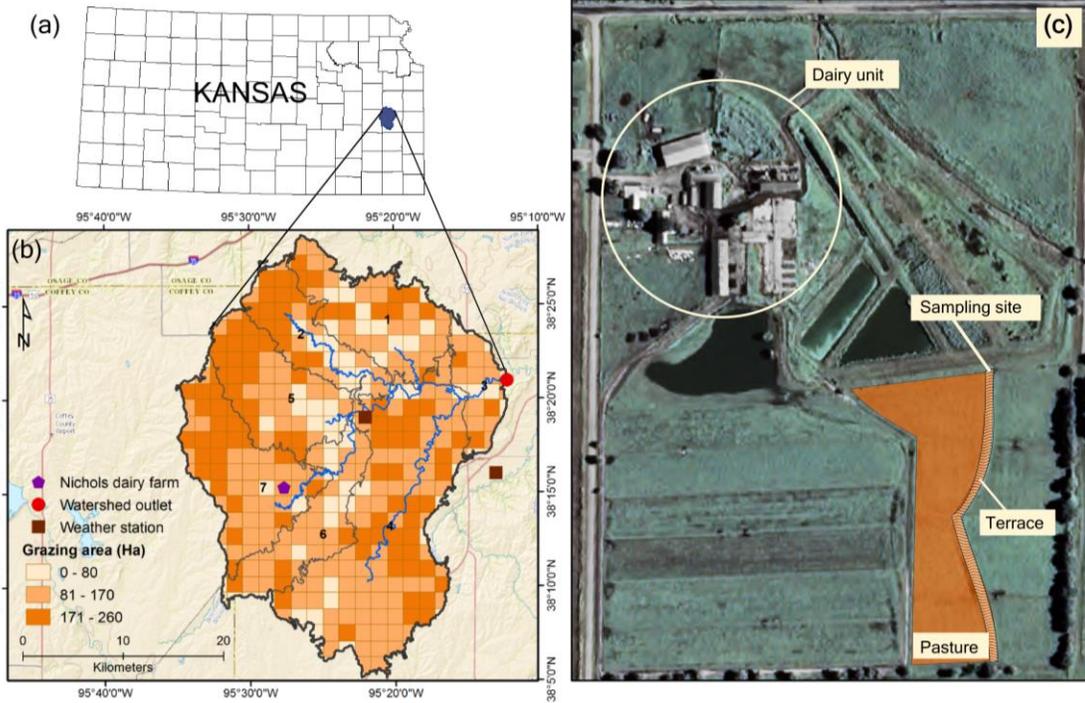
Fig. 1 Study watershed, showing (a) Pottawatomie Creek Watershed in east-central Kansas; (b) stream network, delineated subwatersheds, grazing area in 260-hectare land parcels, weather stations, and USGS gauging station used in streamflow calibration; and (c) aerial image of the Nichols dairy pasture used in sediment and nutrient calibration.

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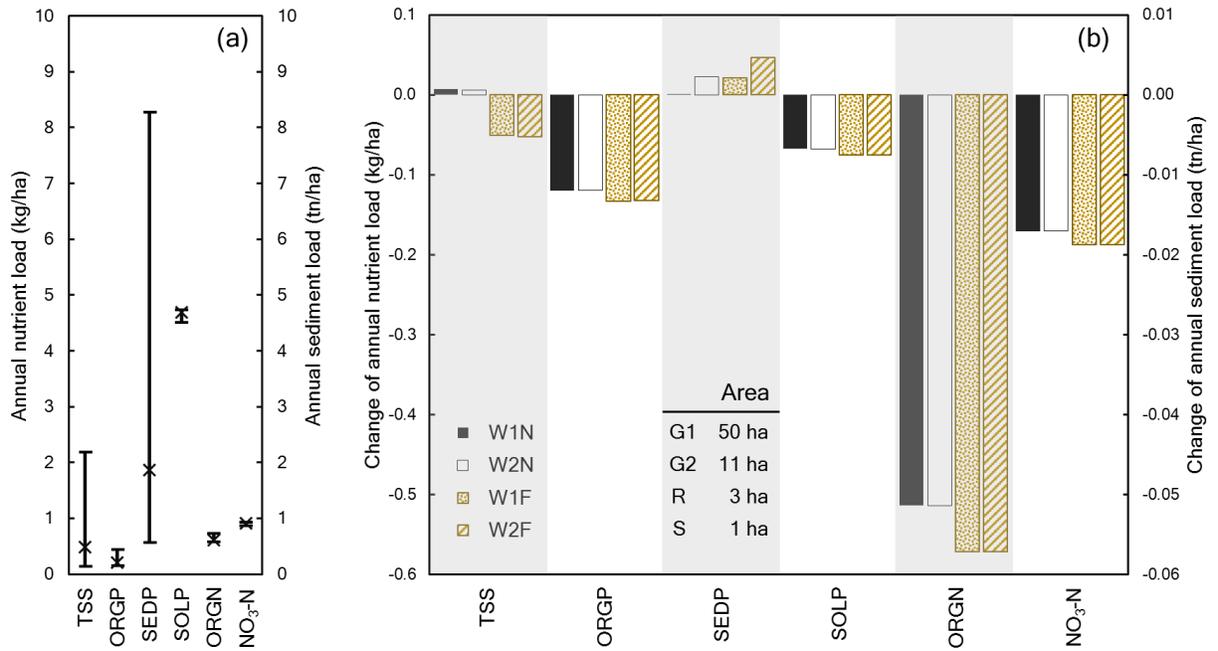
Fig. 2 (a) Annual average loads of total suspended solids (TSS), organic P (ORGP), sediment-attached P (SEDP), soluble P (SOLP), organic N (ORGN), and nitrates (NO₃-N) for baseline scenario of the synthetic pasture, and (b) load changes from the baseline for four BMP scenarios. Subareas G1, G2, R, S were set as default at 50 ha, 11 ha, 3 ha, and 1 ha, respectively, while range bars in (a) represent grazing subarea G1 varying from 0 to 61 ha.
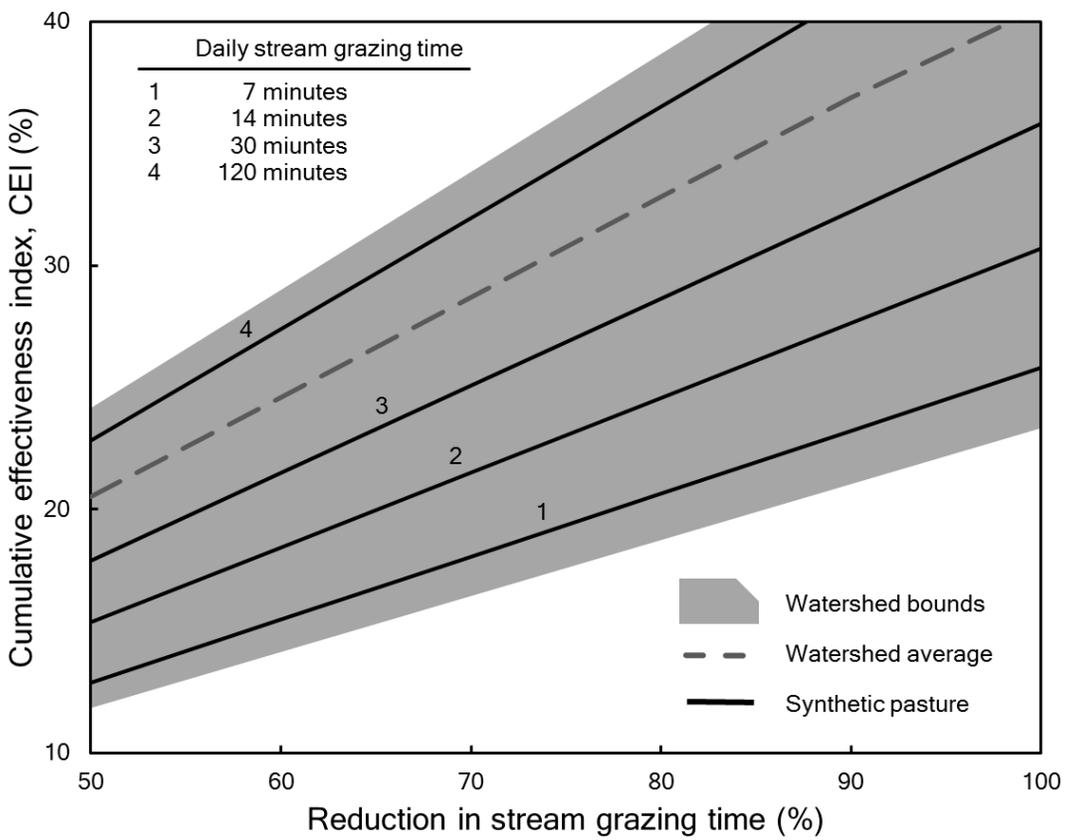
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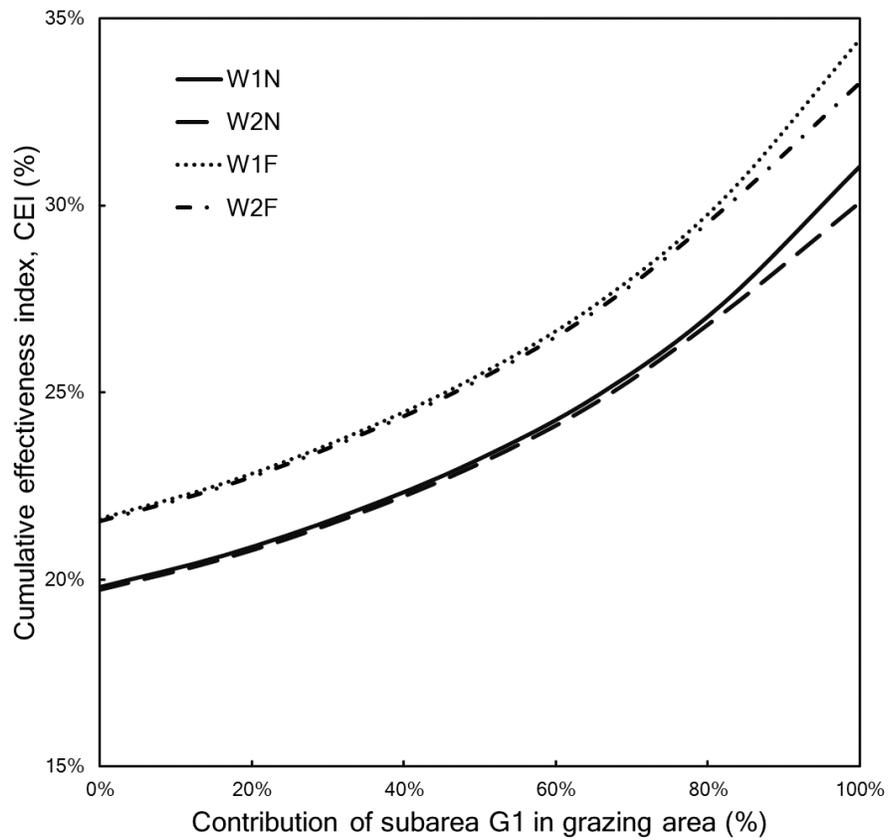
Fig. 3 Pasture BMP cumulative effectiveness index (CEI, %) for four BMP scenarios as a function of the percentage of subarea G1 in total grazing area.

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Fig. 4 BMP cumulative effectiveness index (CEI, %) for W1N scenario in Pottawatomie Creek watershed and
synthetic pasture. The CEI is calculated for various daily stream grazing times as a function of stream time reduction
(based on increasing use of an alternative watering site). The shaded area and dashed line illustrate range and a mean
of CEI for 403 pastures in Pottawatomie Creek watershed, while solid lines show CEI for synthetic pasture.

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555 **Table 1** SWAT management operation input parameters and their values within a grazing land (G1, G2) HRU and a
556 riparian buffer (R) HRU (VAR means variable values).

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Description	SWAT parameter	HRU	Value	Units
Grass type	PLANT_ID	G1,G2	38	—
Management operation	MGT_OP	G1,G2,R	9	—
Type of animals	MANURE_ID	G1,G2,R	9	—
Daily manure	MANURE_KG	G1,G2,R	VAR	kg/ha
Start of grazing	YEAR,MONTH,DAY	G1,G2,R	VAR	—
Number of grazing days	GRZ_DAYS	G1,G2,R	280	Days
Type of fertilizer	FRT_ID	G1,G2	23	—
Amount of fertilizer	FRT_KG	G1,G2	6.8	Kg
Biomass consumed daily	BIO_EAT	G1,G2,R	VAR	kg/ha
Biomass trampled daily	BIO_TRMP	G1,G2,R	VAR	kg/ha
Minimum dry biomass	BIOMIN	G1,G2	500	kg/ha
Initial pasture and buffer conditions	CN2	G1,G2,R	VAR	—

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560 **Table 2** SWAT parameters adjusted during calibration runs in Pottawatomie Creek watershed.

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SWAT parameter	Default value	Range tested	Calibrated value	Description
Streamflow at watershed outlet				
CN2	Varies	67 to 100	-5%	SCS curve number, antecedent moisture condition 2
ESCO	0.95	0 to 1	0.8	Soil evaporation compensation factor
SURLAG	4	1 to 12	1	Surface runoff lag coefficient
CANMX	0	--	Forest: 4.2*	Maximum canopy storage (mm H_2O)
	0	--	Crops: 2.2*	
	0	--	Grass: 3.5*	
RCHRGDP	0.05	0 to 1	1	Deep aquifer percolation factor
SFTMP	1	-5 to 5	-1	Snowfall temperature (°C)
SMTMP	1	-5 to 5	4	Snowmelt temperature (°C)
Pollutant concentrations at pasture edge				
SOL_ORGN	0	850 to 8000	5000**	Initial organic N concentration in soil layer (ppm)
SOL_ORGP	0	150 to 5000	4000***	Initial organic P concentration in soil layer (ppm)
SOL_SOLP	0	250 to 1000	750	Initial soluble P concentration in soil layer (ppm)
BIOMIX	0	0 to 1	0.8	Biological mixing efficiency
BIOMIN	0	0 to 650	500	Minimum plant biomass for grazing (kg/ha)

562 *Ouyang et al. (2010); ** Santhi et al. (2001); *** Richards et al. (2008)

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565 **Table 3** Observed streamflow, pollutant concentrations, and statistics for default and final calibration runs in
566 Pottawatomie Creek watershed (n is the number of samples).

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		NSE	R^2	RSR	PBIAS
Streamflow at watershed outlet					
Mean observed flow (m³/s): 2.67 (Range: 0 - 172.8)					
Default run	Daily	-5.77	0.16	0.08	429.4%
	Monthly	-5.4	0.51	0.42	428.8%
	Annual	-5	0.5	0.3	400.0%
Mean calibrated flow (m³/s): 2.35 (0 - 139.9)					
Calibrated run	Daily	0.59	0.55	0.02	-11.9%
	Monthly	0.83	0.88	0.07	-12.2%
	Annual	0.8	0.85	0.05	-12.1%
Pollutant concentrations at pasture edge (n=22)					
Mean observed concentrations for TSS (tn/ha): 97 (14 - 299); TP (kg/ha): 3.2 (1.0 - 10.6); NO₃-N (kg/ha): 1.3 (0.1 - 3.3)					
Default run	TSS	-0.21	0.2	0.28	-56.9%
	TP	-2	0.01	0.45	-98.9%
	NO₃-N	-1.64	0.01	0.42	8.2%
Mean calibrated concentrations for TSS (tn/ha): 72 (3 - 178); TP (kg/ha): 2.9 (0 - 7.2); NO₃-N (kg/ha): 1 (0 - 5.1)					
Calibrated run	TSS	0.2	0.44	0.23	-25.8%
	TP	-0.78	0	0.33	-8.4%
	NO₃-N	-1	0.05	0.37	-18.9%

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