

# Applicability of the Kostiakov equation to mixed prairie and fescue grasslands of Alberta

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## Abstract

The Kostiakov equation is of interest in rangeland hydrology because it is a simple 2 parameter equation with values of constants easy to determine from measured infiltration data, and because of its reasonable fit to infiltration data for many soils over short time periods. There is, however, some controversy in the literature regarding its applicability to rangelands.

The Kostiakov infiltration equation was examined to determine its suitability to characterize infiltration on mixed prairie and fescue grassland ecosystems in Alberta, Canada. The infiltration data from double ring infiltrometers fit the Kostiakov equation very well. Of 26 regressions, 10 had an  $R^2$  over 0.95 while another 8 had an  $R^2$  over 0.90. The average  $R^2$  for all data at a site was 0.931 for mixed prairie, 0.857 for parkland fescue, and 0.938 for foothills fescue grassland.

Changes in antecedent soil water and different grazing regimes altered the 2 equation parameters. Intercepts consistently declined with intensity and earliness in the growing season of grazing, although there were no consistent treatment trends with grazing. The Kostiakov equation is considered a good equation for infiltration in the 3 grassland ecosystems studied. Although parameter  $m$  had a narrow range of values for all 3 ecosystems and an average value from this study could be used, parameter  $a$  limits the equation and field testing is required for its determination.

**Key Words:** infiltration equation, infiltrometer, rangeland, hydrology

Infiltration is a key hydrologic process partitioning precipitation into soil water and runoff. The ability to model the impacts of grazing on the hydrologic regime is essential for efficient management of rangeland resources. Hydrologic models which can be used in making management decisions require accurate equations for infiltration. Several equations of the infiltration process are available, including Green-Ampt, Horton, Holtan, Philip, and Kostiakov.

The Kostiakov equation is a simple 2 parameter empirical equation (Kostiakov 1932). It relates infiltration to time as a power function:  $f = at^m$  where  $f$  = infiltration capacity;  $t$  = time elapsed since the start of infiltration; and  $a$  and  $m$  are coefficients. In logarithmic form the equation can be written as:  $\log f = \log a + m \log t$ . If  $\log f$  is plotted against  $\log t$ , a straight line should result if Kostiakov's equation applies. The intercept of the equation (infiltration rate at time  $t = 1$ ) is  $a$  and the slope is  $m$ . The lower the value of  $m$ , the flatter the slope and thus the lower the rate of decline of infiltration. The greater the value of  $a$ , the greater the initial infiltration value.

Interest in the Kostiakov equation stems from its simplicity, ease of determining values of the 2 constants from measured infiltration data, and its reasonable fit to infiltration data for many soils over

short time periods (Clemmens 1983). However at long elapsed times, resulting calculated infiltration rates approach zero while actual infiltration rates generally approach a steady value. Kostiakov (1932) indicated that the equation is no longer applicable once the characteristic steady infiltration rate has been attained. This limitation has been circumvented by development of the Kostiakov Branch equation which is useful for analyzing distribution uniformity, although determining constants becomes more difficult than with the simple Kostiakov formulation (Clemmens 1983). Another modification is to add constant infiltration rate to that calculated at all times.

Clemmens (1983) found the Kostiakov equation significantly better than the theoretical equations of Philip and Green-Ampt for border irrigation infiltration data. The  $r^2$  values were 0.950 for cumulative infiltration data sets, 0.856 for cumulative infiltration data sets from infiltration rings, and 0.727 for infiltration rate data from infiltration rings. Clemmens (1983) concluded that for most situations the simple Kostiakov equation was adequate to describe infiltration and when not adequate he recommended the Modified or Branch Kostiakov models which can account for a constant final infiltration rate.

Gifford (1976) found the Kostiakov equation did not fit infiltrometer data collected from semiarid rangelands in Australia or the United States.  $R^2$  values ranged from 0.48 for data from Australia to 0.13 for data from southern Utah. He found no consistent influence of antecedent moisture conditions on  $R^2$  values. Gifford (1978) concluded coefficients in Kostiakov's equation were related more to vegetation factors than to soil factors based on infiltrometer data run with soils pre-wet to field capacity prior to the infiltration test. Haverkamp et al. (1987) stated that although the Kostiakov equation showed a high level of precision up to the time limit, its application to predictive use becomes highly erroneous because of the reduction in precision with time, especially in coarse-textured soils.

The objective of this study was to investigate the suitability of the Kostiakov equation for characterizing infiltration data from double ring infiltrometers in mixed prairie and fescue grassland ecosystems of Alberta. The Kostiakov equation was chosen because of simplicity and the controversy in the literature surrounding its use in rangelands. In grassland ecosystems of Alberta, ponded infiltration conditions are believed to suitably represent natural conditions of generally low rainfall intensities and snowmelt. Vegetative cover and litter are generally high enough (Naeth 1988) to minimize the detrimental effects of raindrop impact on infiltration.

## Materials and Methods

### Study Sites

Three study sites representing major rangeland ecosystems of southern and central Alberta were selected. Each site had long-term grazing treatments, ungrazed controls, grass-dominated vegetation that had never been cultivated, and slopes of less than 2% (Naeth 1988).

The mixed prairie site was located near Brooks approximately 225 km east of Calgary (51° N and 112° W). The area has a

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continental prairie climate and a semiarid moisture regime. Mean annual precipitation is 355 mm. Mean annual temperature is 4° C, with a July mean of 19° C and a January mean of -14° C. Elevation averages 745 m above sea level with slopes of less than 2%. Soils are Brown Solodized Solonetz and Brown Solod (Natriboroll) developed on till (Kjearsgaard et al. 1982). Soil was loam textured in the uppermost 30 cm and clay loam below. Vegetation is of the Blue grama-Spear grass-Wheat grass (*Bouteloua-Stipa-Agropyron*) faciation, dominated by blue grama grass (*Bouteloua gracilis* Lag.), spear grass (*Stipa comata* Trin. & Rupr.), and western and northern wheat grasses (*Agropyron smithii* Rydb. and *dasystachyum* Hook.). Pasture sage (*Artemisia frigida* Willd.) and little clubmoss (*Selaginella densa* Rydb.) are common forbs. A short grass disclimax dominated by blue grama is common as a result of heavy long-term grazing.

The parkland fescue site was located near Kinsella approximately 150 km southeast of Edmonton (53° N and 111° W). The climate is dry subhumid. Mean annual precipitation is 422 mm. Mean annual temperature is 2° C, with a July mean of 17° C and a January mean of -17° C. Elevation averages 685 m above sea level with gently rolling to hilly topography (Howitt 1988). Grassland soils are dominated by Orthic Black Chernozems (Cryoboroll) developed on till. Soil was sandy clay loam textured in the uppermost 5 cm and loam to sandy loam below. Vegetation consists of grass and shrub communities with aspen groves occurring at irregular intervals. Rough fescue (*Festuca hallii* Vasey Piper) (Pavlick and Looman 1984) dominates open undisturbed grasslands and western porcupine grass (*Stipa curtisetata* Hitchc.) co-dominates on grazed areas. Forbs are a common component of the vegetation.

The foothills fescue grassland site was located near Stavely approximately 100 km south-southwest of Calgary (50° N and 114° W). The climate is subhumid without marked deficiency of precipitation. Mean annual precipitation is 550 mm. Mean annual temperature is 5° C, with a July mean of 18° C and a January mean of -10° C. Elevation averages 1,350 m above sea level and topography is gently rolling to hilly. Soils are Orthic Black Chernozems (Haploboroll) developed on till (Johnston et al. 1971). Soils were clay loam textured in the uppermost 30 cm and loam to clay loam below (Naeth 1988). Vegetation is of the fescue grassland association with rough fescue (*Festuca campestris* Rydb.) dominating in the undisturbed and lightly grazed areas. Parry's oat grass (*Darthonia parryi* Scribn.) and bluebunch fescue (*Festuca idahoensis* Elmer) are co-dominants in grazed areas. Under heavy grazing regimes, rough fescue is replaced by annual invaders and bluegrass (*Poa* L.) species.

#### Grazing Treatments

In mixed prairie, 3 grazing treatments were studied within a community pasture established in 1964: (1) early season grazing from May through July; (2) late season grazing from August through October; and (3) a control ungrazed since the late 1930s. The stocking rate was heavy at 0.9 AUM ha<sup>-1</sup>. There was 7.0% bare ground under early season grazing, 4.0% under late season grazing, and 1.5% in the control.

In parkland fescue, 5 grazing treatments established in 1973 on the University of Alberta ranch were studied: (1) light June grazing from June 1 to 30 at 1.5 AUM ha<sup>-1</sup>; (2) heavy June grazing from June 1 to 30 at 4.4 AUM ha<sup>-1</sup>; (3) heavy autumn grazing from 15 September to 15 October at 4.4 AUM ha<sup>-1</sup>; (4) light autumn grazing from 15 September to 15 October at 1.5 AUM ha<sup>-1</sup>; and (5) a control ungrazed since 1942 (Bailey et al. 1987). There was 0.0% bare ground under light June grazing, light autumn grazing, and the control, 2.0% under heavy June grazing, and 0.5% under heavy autumn grazing.

In foothills fescue, 5 grazing treatments established in 1949 on the Agriculture Canada Range Research Substation and grazed

May through September were studied: (1) very heavy grazing at 4.8 AUM ha<sup>-1</sup>; (2) heavy grazing at 2.4 AUM ha<sup>-1</sup>; (3) moderate grazing at 1.6 AUM ha<sup>-1</sup>; (4) light grazing at 1.2 AUM ha<sup>-1</sup>; and (5) a control comprised of permanent exclosures in each treatment (Johnston et al. 1971). There was 14.5% bare ground under very heavy grazing, 10.5% under heavy grazing, 1.0% under moderate grazing, 0.5% under light grazing, and 0.0% in the control.

#### Infiltration Tests

Infiltration data were collected in late July 1985 and 1986 using double ring infiltrometers with outside diameters of approximately 63 cm and inside ring diameters of approximately 33 cm. Water was added to the rings to maintain a head of 5 to 8 cm. Float readings were started the first minute after the rings were filled. Subsequent readings were taken every minute in the first 5 minutes, at 7 minutes, at 10 minutes, and every 5 minutes thereafter until a steady rate was achieved. The tests were usually terminated after 1 hour. Six infiltration tests in 1985 and 9 in 1986 were conducted in each treatment at each site, except in the Stavely control in 1986 when 12 tests were conducted.

Soil water and bulk density for the uppermost 7.5 cm were measured immediately adjacent to the rings at the time of the infiltration tests using a surface/moisture density gauge. Degree of saturation (%) at the time of infiltration was calculated using bulk density and soil water, assuming a particle density of 2.65 Mg m<sup>-3</sup>. A best fit regression line for the averaged data was fit for log infiltration rate versus log time, up to an elapsed time of 40 min, and slope intercept of the regression lines were determined.

#### Results and Discussion

Near-surface soil bulk densities in parkland fescue and foothills fescue were less than 1.00 Mg m<sup>-3</sup>, with soil porosities of 60 to 70%. Bulk densities in mixed prairie were slightly higher, averaging 1.10 Mg m<sup>-3</sup>, with porosities of 56 to 61%. Degrees of soil saturation at the time of the infiltration tests were higher in 1986 than in 1985 (Table 1).

Table 1. Degree of saturation (%) at time of infiltration tests.

Site	Grazing Treatment	Year	
		1985	1986
Mixed Prairie	Early Season	18.5	24.0
	Late Season	16.0	28.1
	Control	22.4	26.3
Parkland Fescue	Light June	48.9	67.0
	Heavy June	50.5	66.2
	Heavy Autumn	44.3	61.6
	Light Autumn	26.0	58.1
	Control	27.4	46.5
Foothills Fescue	Very Heavy	24.9	26.0
	Heavy	24.7	31.0
	Moderate	22.7	29.0
	Light	23.0	33.1
	Control	21.8	28.9

The Kostiakov equation fit double ring infiltration data from the 3 ecosystems very well (Fig. 1). Of 26 regressions, 10 had an R<sup>2</sup> over 0.95 while another 8 had an R<sup>2</sup> over 0.90. The average R<sup>2</sup> for all data at a site was 0.931 for mixed prairie, 0.857 for parkland fescue, and 0.938 for foothills fescue. The lower R<sup>2</sup> values for parkland fescue are likely due to soil profile heterogeneity caused by a gravelly layer at a depth of approximately 10 cm.

Infiltration capacity generally decreases with increased grazing intensity and reduced range condition (Blackburn 1984). In the 3

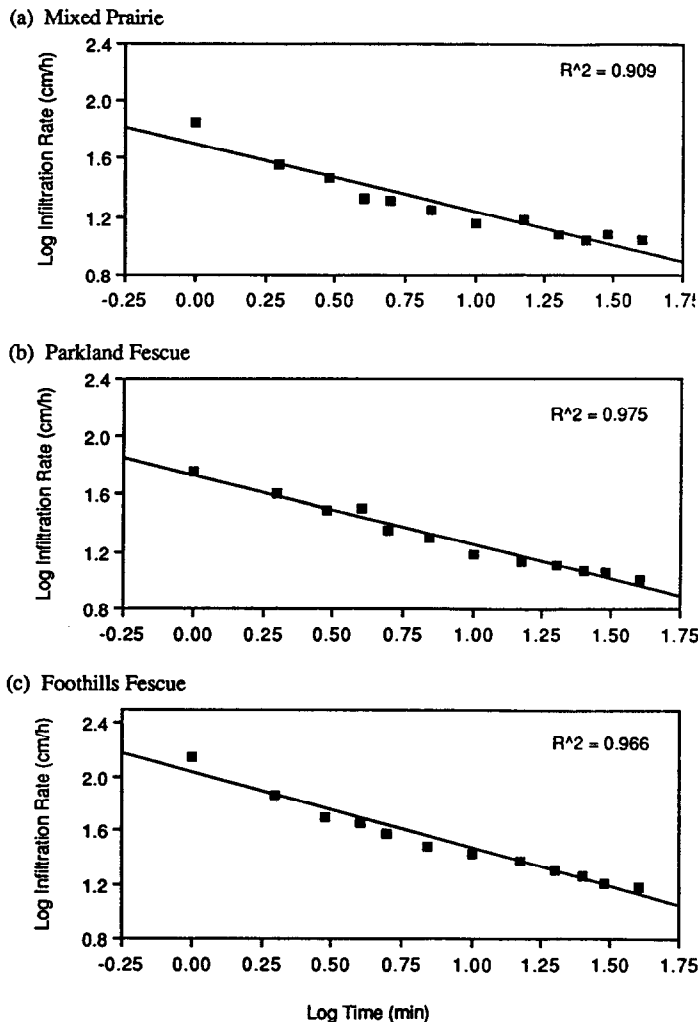


Fig. 1. Best fit infiltration line for averaged data from the ungrazed controls in (a) mixed prairie, (b) parkland fescue, and (c) foothills fescue in 1985.

study sites, infiltration capacity was affected by grazing intensity and season of grazing, being lower under early season and/or heavy intensity treatments than under late season and/or light intensity treatments (Naeth 1988). The Kostiakov equation was sensitive to these changes in infiltration capacity brought about through grazing treatments. Both intercepts and slopes in all 3 grasslands were affected by grazing treatment and antecedent soil water. In mixed prairie the lowest slopes were in the control, with the lowest intercepts in the early season grazed treatment (Table 2). In parkland fescue the lowest slopes were in the heavy June grazed treatment and the lowest intercepts were in the light June or heavy

Table 2. Infiltration equation parameters and  $R^2$  values for mixed prairie.

Year	Parameter	Early Season Grazed	Late Season Grazed	Control (Ungrazed)
1985	slope (m)	-0.495	-0.573	-0.437
	intercept (a)	36.3	46.3	43.7
	$R^2$	0.952	0.951	0.869
1986	slope (m)	-0.522	-0.531	-0.447
	intercept (a)	37.7	47.0	49.0
	$R^2$	0.951	0.951	0.910

June grazed treatments (Table 3). In foothills fescue the lowest slopes were in the light grazed treatment and the lowest intercept was in the very heavy grazed treatment (Table 4). Intercept consistently declined with intensity and earliness in the growing season of grazing for all 3 ecosystems. There were no consistent treatment trends for slopes.

Table 3. Infiltration equation parameters  $R^2$  values for parkland fescue.

Year	Parameter	Light June Grazed	Heavy June Grazed	Heavy Autumn Grazed	Light Autumn (Ungrazed) Grazed	Control
1985	slope (m)	-0.655	-0.364	-0.537	-0.476	-0.496
	intercept (a)	43.8	27.7	49.1	51.9	55.2
	$R^2$	0.907	0.803	0.879	0.892	0.974
1986	slope (m)	-0.494	-0.189	-0.309	-0.354	-0.316
	intercept (a)	13.4	13.6	18.5	23.8	22.9
	$R^2$	0.843	0.680	0.850	0.934	0.804

The influence of increasing soil water on both slope and intercept is dramatically shown for parkland fescue. The average reduction in slope was 35% and average reduction in intercept was 59% for an increase in average degree of soil saturation from 39.4 to 60.0% (Table 3). Greatest year-to-year soil water differences at the time of the infiltration tests were in the light autumn treatment in parkland fescue (Table 1). The 227% increase in soil water reduced the intercept by 54% and the slope by 25% (Fig. 2 and Table 3).

In 1985, degree of soil saturation in foothills fescue at the time of the infiltration tests was similar for all treatments (Table 1).  $R^2$  of 0.973, 0.916, and 0.942 were obtained for the fit of the Kostiakov equation in the very heavy grazed, light grazed, and control treatments, respectively (Fig. 3). Slopes were not dramatically different among treatments, but the intercepts declined from 105.7 to 48.4  $\text{cm h}^{-1}$  as grazing intensity increased (Table 4). Data for the very heavy grazed treatment in foothills fescue for the 2 study years can be used to indicate possible year-to-year variation in equation parameters (15% for slope and 16% for intercept) since degree of soil saturation for this treatment in both years was similar (24.9% versus 26.0%).  $R^2$  were identical for both years (Table 4).

The range of values for m for all 3 ecosystems was narrow (Tables 2, 3, and 4). From a modelling perspective this is important in that an average value for m obtained from this study could be

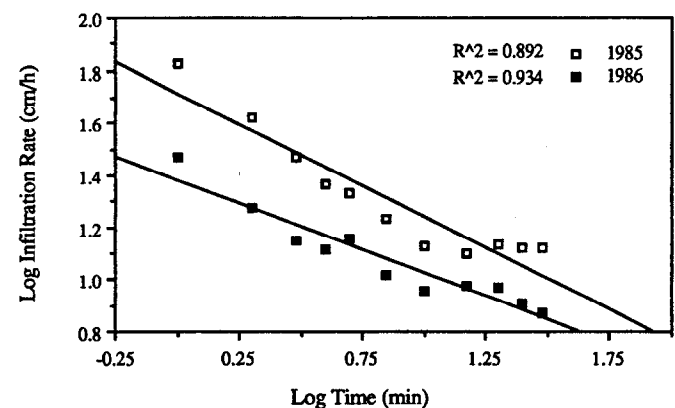


Fig. 2. Infiltration under light autumn grazing in parkland fescue in 1985 and 1986.

**Table 4. Infiltration equation parameters  $R^2$  values for foothills fescue.**

Year	Parameter	Very Heavy Grazed	Heavy Grazed	Moderate Grazed	Light Grazed	Control (ungrazed)
1985	slope (m)	-0.453	-0.598	-0.497	-0.436	-0.561
	intercept (a)	48.4	61.1	71.3	73.8	105.7
	$R^2$	0.973	0.935	0.921	0.916	0.942
1986	slope (m)	-0.519	-0.624	-0.575	-0.444	-0.493
	intercept (a)	40.8	54.6	56.4	58.3	84.3
	$R^2$	0.974	0.942	0.960	0.927	0.925

used. However, this not true for a since this parameter varies quite dramatically with soil water and intensity and season of grazing. As a result parameter a becomes the limiting parameter and field testing is required for its determination.

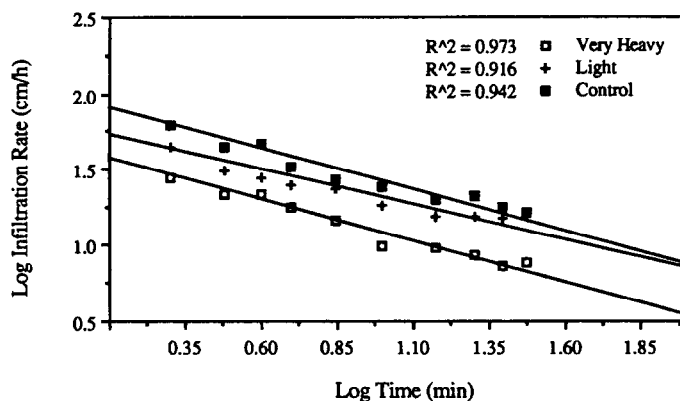
These results do not support the work of Gifford (1976), who found the Kostikov equation did not fit infiltration data for the United States and Australian rangelands. This discrepancy may be due to the differences in the ecosystems or to the fact that data from double ring infiltrometers were evaluated in this study, whereas Gifford used data obtained from rainfall simulators. Differences in pre-treatment strategies may also have contributed to the discrepancy. Some of Gifford's tests were pre-wet and others were not. All tests in this study were run at field water contents to reflect field conditions. Also in this study, infiltration rates were determined directly; in Gifford's study infiltration rates were calculated by difference.

### Conclusions

The infiltration data from mixed prairie and fescue grassland ecosystems of Alberta fit the Kostikov equation quite well. Changes in antecedent soil water and intensity and season of grazing affected the intercept much more than the slope. Intercepts consistently declined with intensity and earliness in the growing season of grazing, although there were no consistent treatment trends for slopes.

### References

Bailey, A.W., M.G. Willoughby, and B.D. Irving. 1987. Effect of grazing on forage and beef production from rough fescue rangeland in central Alberta. Farming for the Future Final Rep Proj. 84-0335.



**Fig. 3. Infiltration in foothills fescue in 1985 in the very heavy grazed, light grazed, and control treatments.**

Blackburn, W.H. 1984. Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses. P. 927-983 *In: Developing strategies for rangeland management.* NRC/NAS. Westview Press/Boulder and London.

Clemmens, A.J. 1983. Infiltration equations for border irrigation models. P. 266-274. *In: Advances in infiltration. Proc. Nat. Conf. on Advances in Infiltration.* Dec. 12-13, 1983. Chicago, Ill. ASAE Pub. 11-83. St. Joseph Mo.

Gifford, G.F. 1976. Applicability of some infiltration formulae to rangeland infiltrometer data. *J. Hydrol.* 28:1-11.

Gifford, G.F. 1978. Use of infiltration equation coefficients as an aid in defining hydrologic impacts of range management schemes. *J. Range Manage.* 31:115-117.

Haverkamp, R., L. Rendon, G. Vachaud. 1987. Infiltration equations and their applicability for predictive use. P. 142-152. *In: Infiltration development and application. Proc. Internat. Conf. Infiltration Development and Application.* Yu-SI Fok (ed.). Jan. 6-9, 1987. Honolulu, Hawaii.

Howitt, R.W. 1988. Soil survey of the county of Beaver. Alberta Soil Survey Rep. 47. Alberta Research Council Open File Rep. 1987-4.

Johnston, A., J.F. Dormaar, and S. Smoliak. 1971. Long-term grazing effects on fescue grassland. *J. Range Manage.* 24:185-188.

Kjarsgaard, A.A., W. Peters, and W.W. Pettapiece. 1982. Soil survey of the County of Newell No. 4, Alberta. Alberta Institute of Pedology Rep. S-82-41.

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

Naeth, M.A. 1988. The impact of grazing on litter and hydrology in mixed prairie and fescue grassland ecosystems of Alberta. Ph.D. thesis. Univ. Alberta, Edmonton.

Pavlick, L.E., and J. Looman. 1984. Taxonomy and nomenclature of rough fescues, *Festuca altaica*, *Festuca campestris* (*F. scabrella* var. major), and *Festuca hallii*, in Canada and the adjacent part of the United States. *Can. J. Bot.* 62:1739-1749.