

**Modelling  
Climate – Surface Hydrology  
Interactions in Data Sparse Areas**

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The IHACRES rainfall-runoff model, which formed the basis of the rainfall-runoff model developed within, was originally developed by Prof. Anthony Jakeman. This work has not previously been submitted for a degree or diploma in any institution of higher education.

Some of the work presented in Chapter 4 has previously been published in Evans and Jakeman (1997, 1998); some of the work from Chapter 8 has been published in Evans et al. (1999); and some of the work from Chapter 9 has been published in Evans et al. (2000). Any contributions made by co-authors are indicated in the text.

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## *Abstract*

The interaction between climate and land-surface hydrology is extremely important in relation to long term water resource planning. This is especially so in the presence of global warming and massive land use change, issues which seem likely to have a disproportionate impact on developing countries. This thesis develops tools aimed at the study and prediction of climate effects on land-surface hydrology (in particular streamflow), which require a minimum amount of site specific data. This minimum data requirement allows studies to be performed in areas that are data sparse, such as the developing world.

A simple lumped dynamics-encapsulating conceptual rainfall-runoff model, which explicitly calculates the evaporative feedback to the atmosphere, was developed. It uses the linear streamflow routing module of the rainfall-runoff model IHACRES, with a new non-linear loss module based on the Catchment Moisture Deficit accounting scheme, and is referred to as CMD-IHACRES. In this model, evaporation can be calculated using a number of techniques depending on the data available, as a minimum, one to two years of precipitation, temperature and streamflow data are required. The model was tested on catchments covering a large range of hydroclimatologies and shown to estimate streamflow well. When tested against evaporation data the simplest technique was found to capture the medium to long term average well but had difficulty reproducing the short-term variations.

A comparison of the performance of three limited area climate models (MM5/BATS, MM5/SHEELS and RegCM2) was conducted in order to quantify their ability to reproduce near surface variables. Components of the energy and water balance over the land surface display considerable variation among the models, with no model performing consistently better than the other two. However, several conclusions can be made. The MM5 longwave radiation scheme performed worse than the scheme implemented in RegCM2. Estimates of runoff displayed the largest variations and differed from observations by as much as 100%. The climate models exhibited greater variance than the observations for almost all the energy and water related fluxes investigated.

An investigation into improving these streamflow predictions by utilizing CMD-IHACRES was conducted. Using CMD-IHACRES in an “offline” mode greatly improved the streamflow estimates while the simplest evaporation technique reproduced the evaporative time series to an accuracy comparable to that obtained from the limited area models alone. The ability to conduct a climate change impact study using CMD-IHACRES and a stochastic weather generator is also demonstrated. These results warrant further investigation into incorporating the rainfall-runoff model CMD-IHACRES into a limited area climate model in a fully coupled “online” approach.



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## *List of Symbols*

<i>Symbol</i>	<i>Meaning</i>	<b>Units</b>
$\sim$	denotes an environmental value	-
$\alpha$	represents an arbitrary variable; also absorptivity	-
$\alpha_c$	cloud water radiation absorption coefficient	$\text{m}^2\text{g}^{-1}$
$\alpha_{cd}$	cloud water downward radiation absorption coefficient	$\text{m}^2\text{g}^{-1}$
$\alpha_{cu}$	cloud water upward radiation absorption coefficient	$\text{m}^2\text{g}^{-1}$
$\alpha_i$	cloud ice radiation absorption coefficient	$\text{m}^2\text{g}^{-1}$
$\alpha_p$	radiation absorption coefficient for precipitation	$\text{m}^2\text{g}^{-1}$
$\beta$	fraction of updraft condensate that re-evaporates in the downdraft	-
$\delta\theta$	soil moisture	mm
$\Delta = \frac{de^*}{dT}$	slope of the saturation water vapour pressure curve	$\text{mbK}^{-1}$
$\Delta s$	model gridpoint spacing	m
$\Delta t$	model time step	s
$\epsilon_d$	downward emissivity function	-
$\epsilon_{tot}$	total emissivity	-
$\epsilon_u$	upward emissivity function	-
$\epsilon_{vapour}$	water vapour emissivity	-
$\phi_0$	soil water suction for saturated soil	m
$\phi_m$	wind profile function	-
$\gamma$	psychrometric constant	$\text{mbK}^{-1}$
$\gamma_\xi$	correction to the local gradient that incorporates the contribution of large scale eddies to the total flux	-

$\eta$	fraction of transpiration from the top soil layer	-
$\mu$	cosine of the zenith angle	-
$\tilde{\nu}$	wavenumber	$\text{m}^{-1}$
$\nu_a$	annual frequency	$\text{s}^{-1}$
$\nu_d$	diurnal frequency	$\text{s}^{-1}$
$\theta$	potential temperature	K
$\theta_s$	appropriate near surface temperature	K
$\theta_v$	virtual potential temperature	K
$\theta_{va}$	virtual potential temperature at the lowest model level	K
$\rho$	density	$\text{kgm}^{-3}$
$\rho_a$	density of surface air	$\text{kgm}^{-3}$
$\rho_r$	particle density	$\text{kgm}^{-3}$
$\rho_s$	density of the subsurface soil layer	$\text{kgkg}^{-1}$
$\rho_w$	soil water density	$\text{kgkg}^{-1}$
$\rho_{wsat}$	saturated soil water density	$\text{kgkg}^{-1}$
$\sigma$	terrain following vertical coordinate	
$\sigma_f$	fractional foliage cover for each grid point	-
$\sigma_{SB}$	Stefan-Boltzmann constant	$\text{Wm}^{-2}\text{K}^{-4}$
$\tau_c$	cloud extinction optical depth	m
$\tau_q$	quickflow time constant	days
$\tau_s$	slowflow time constant	days
$\omega$	particle single scattering albedo	
$\Omega_{r0}$	maximum transpiration that can be sustained	$\text{kgm}^{-2}\text{s}^{-1}$
$\xi$	represents a prognostic variable	-
$\psi_{w1}$	diffusion of water from rooting zone to surface soil layer	$\text{mms}^{-1}$
$\psi_{w2}$	diffusion of water from total column to rooting zone	$\text{mms}^{-1}$
$\Psi_w$	rate of transfer of water by diffusion to the upper soil layer	$\text{mms}^{-1}$
$a$	Marshall-Palmer distribution parameter	-
$A$	surface area	$\text{m}^2$

$A_{\bar{\nu}}$	absorptivity due to a given gas	-
$ABE$	buoyant energy available	J
$ABE''$	production of available buoyant energy by large scale motions during the time $\Delta t$	J
$b$	Marshall-Palmer distribution parameter	-
$B$	Plank function; also Clapp and Hornberger exponent	-
$B$	bias	mm/day
$B_0$	Bowen ration	-
$C_D$	aerodynamic drag coefficient over land	-
$C_{DN}$	drag coefficient for neutral stability	-
$CMD$	catchment moisture deficit	mm
$C_p$	specific heat of air	$\text{Jkg}^{-1}\text{K}^{-1}$
$C_s$	specific heat of the subsurface soil layer	$\text{Jkg}^{-1}\text{K}^{-1}$
$C_{SOILC}$	transfer coefficient between canopy air and underlying soil	-
$D$	diameter of droplet; relative drying power; also discharge from catchment	m; - ; mm
$D_{db}$	diurnal penetration depth	m
$D_f$	characteristic dimension of the leaves in the direction of wind flow	-
$D_s$	water diffusivity in the soil	$\text{m}^2\text{s}^{-1}$
$D_w$	rate of excess water dripping from leaves per unit land area	$\text{mm m}^{-2}$
$E$	evapotranspiration	mm
$e_a$	vapour pressure in near surface atmosphere	mb
$E_a$	total evaporative flux from the surface to the atmosphere	$\text{kgm}^{-2}\text{s}^{-1}$
$E_A$	drying power of the air	mm
$E_f$	evaporative flux from foliage	$\text{kgm}^{-2}\text{s}^{-1}$
$E_f^{WET}$	evaporation from wet foliage per unit wetted area	$\text{kgm}^{-2}\text{s}^{-1}$
$E_g$	evaporative flux from the ground	$\text{kgm}^{-2}\text{s}^{-1}$
$E_p$	potential evapotranspiration	mm
$E_{p0}$	evapotranspiration rate at which $E_p=E$	mm

$E_{PT}$	Priestly & Taylor potential evapotranspiration	mm
$e_s^*$	saturation vapour pressure at the surface temperature	mb
$E_{tr}$	transpiration	mm
$E_{trmax}$	maximum transpiration	$\text{kgm}^{-2}\text{s}^{-1}$
$F^\uparrow$	upward long wave radiation flux	$\text{Wm}^{-2}$
$F^\downarrow$	downward long wave radiation flux	$\text{Wm}^{-2}$
$f_{cld}$	probability of a cloud existing in a given atmospheric layer	-
$f_{clear}$	clear sky fraction of atmospheric column	-
$F_{clr}^\downarrow$	clear sky downward longwave radiation	$\text{Wm}^{-2}$
$F_{clr}^\uparrow$	clear sky upward longwave radiation	$\text{Wm}^{-2}$
$f_g$	wetness factor	-
$F_H$	horizontal diffusion effects	
$F_q$	moisture flux from ground to atmosphere	$\text{kgm}^{-2}\text{s}^{-1}$
$F_{qm}$	maximum moisture flux through the wet surface that the soil can sustain	$\text{kgm}^{-2}\text{s}^{-1}$
$F_{qp}$	potential evaporation	$\text{kgm}^{-2}\text{s}^{-1}$
$F_{rr}$	the unfrozen soil water	mm
$F_s$	atmospheric sensible heat flux	$\text{Wm}^{-2}$
$F_V$	vertical turbulent mixing effects	
$g$	gravity ( $\text{ms}^{-2}$ ); also asymmetry parameter	-
$G$	net water applied to the surface in the absence of vegetation; also specific flux of heat into the ground	mm; $\text{Wm}^{-2}$
$h$	moist static energy; also height of PBL (m)	-
$H_a$	total sensible heat flux from the surface to the atmosphere	$\text{Wm}^{-2}$
$H_f$	sensible heat flux from foliage	$\text{Wm}^{-2}$
$H_g$	sensible heat flux from the ground	$\text{Wm}^{-2}$
$h_l$	meridionally varying, empirically derived local liquid water scale	-
$h_s$	surface heating	$\text{Wm}^{-2}$
$I_l$	amount of condensation integrated over the whole depth	-

	of the updraft normalised by the updraft mass flux	
$I_2$	evaporation in the downdraft normalised by the downdraft mass flux	-
$J$	relative evaporation; also Thornthwaite heat index	-
$k$	von Karman constant	-
$K_\xi$	the eddy diffusivity coefficient	$\text{m}^2\text{s}^{-1}$
$k_{sb}$	thermal diffusivity of soil for diurnal wave	$\text{m}^2\text{s}^{-1}$
$K_{w0}$	saturated hydraulic conductivity	$\text{ms}^{-1}$
$K_{zm}$	momentum diffusivity coefficient at height $z$ above the surface	$\text{m}^2\text{s}^{-1}$
$K_{zm}$	eddy diffusivity for moisture at height $z$ above the surface	$\text{m}^2\text{s}^{-1}$
$K_{zt}$	eddy diffusivity for temperature at height $z$ above the surface	$\text{m}^2\text{s}^{-1}$
$L$	latent heat; Monin-Obukhov length scale; also daytime hours	$\text{Wm}^{-2}$ ; - ; 12 hrs
$L_{AI}$	leaf area index	-
$L_d$	fraction of foliage surface free to transpire	-
$L_e$	latent heat of evaporation	$\text{Wm}^{-2}$
$L_f$	latent heat of fusion	$\text{Jkg}^{-1}$
$L_s$	latent heat of sublimation	$\text{Jkg}^{-1}$
$LS$	denotes the large scale tendency	-
$L_v$	latent heat of vaporisation	$\text{Jkg}^{-1}$
$L_w$	fractional area of leaves and stems covered by water	-
$M$	moisture availability parameter	-
$m_0$	mass flux at the downdraft originating level	$\text{kgm}^{-2}\text{s}^{-1}$
$m_b$	mass flux at the updraft originating level	$\text{kgm}^{-2}\text{s}^{-1}$
$MC$	denotes the model calculated tendency	-
$m_d$	mass flux of the downdraft	$\text{kgm}^{-2}\text{s}^{-1}$
$M_f$	stomatal resistance dependence on soil moisture	-
$m_u$	mass flux of the updraft	$\text{kgm}^{-2}\text{s}^{-1}$
$n$	the displacement from the nearest boundary	grid points
$N_0$	Marshall-Palmer distribution parameter	$\text{m}^{-4}$

$NA$	rate of change of available buoyant energy per unit of mass flux	$\text{Js}^{-1}$
$NSE$	Nash-Sutcliffe efficiency	-
$p$	pressure	Pa
$P$	precipitation	mm
$p^*$	$p_s - p_{top}$	Pa
$p_{clbk}$	pressure level of the cloud base at k	Pa
$P_{CON}$	condensation of water vapour into cloud	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{ID}$	sublimation/deposition of cloud ice	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{II}$	initiation of ice crystals	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{MF}$	melting (freezing) of snow or ice (rain or cloud) due to atmospheric advection	$\text{kgkg}^{-1}\text{s}^{-1}$
$Pr$	Prandtl number	-
$P_r$	precipitation falling as rain	mm
$P_{RA}$	accretion of cloud by rain	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{RC}$	conversion of cloud to rain	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{RE}$	evaporation of rain	$\text{kgkg}^{-1}\text{s}^{-1}$
$P_{RM}$	snow melting to become rain	$\text{kgkg}^{-1}\text{s}^{-1}$
$p_s$	prognostic surface pressure	Pa
$p_{top}$	pressure specified to be the model top	Pa
$q$	specific humidity; also streamflow (observed)	$\text{kgkg}^{-1}$ ; mm
$\hat{q}$	modelled streamflow	mm
$q_a$	specific humidity of the lowest model level	-
$q_{af}$	water vapour specific humidity of the air within the foliage	-
$q_c$	mixing ratio of cloud water	-
$q_g$	saturated specific humidity at the temperature of the surface	-
$Q_g$	net outflow of ground water	mm
$q_{g,s}$	saturated specific humidity at soil surface temperatures	-
$Q_n$	available energy flux density	$\text{Wm}^{-2}$



$q_r$	mixing ratio of rain water	-
$Q_s$	net outflow of surface water	mm
$q_v$	mixing ratio of water vapour	-
$\mathcal{R}$	residual of water balance	mm
$r_e$	effective of cloud droplets	m
$R_f$	stomatal resistance dependence on solar radiation	-
$R_g$	groundwater runoff	mm
$Ri_B$	surface bulk Richardson number	-
$Rib_{cr}$	critical bulk Richardson number	-
$r_{la}$	aerodynamic resistance to moisture and heat flux	$\text{sm}^{-1}$
$R_{net}$	net incident radiation at the surface	$\text{Wm}^{-2}$
$r_s$	stomatal resistance	$\text{sm}^{-1}$
$R_s$	surface runoff	mm
$r_{smin}$	minimum stomatal resistance	$\text{sm}^{-1}$
$R_{ti}$	fraction of roots in soil layer i	-
$s$	volume of water divided by volume of water at saturation	-
$S$	sources and sinks; also water volume stored in the system	- ; mm
$S_0$	solar constant	$\text{Wm}^{-2}$
$S_a$	clear air absorption of shortwave radiation flux	$\text{Wm}^{-2}$
$S_{AI}$	stem area index	-
$S_{ca}$	cloud absorption of shortwave radiation flux	$\text{Wm}^{-2}$
$S_{cs}$	cloud scattering of shortwave radiation flux	$\text{Wm}^{-2}$
$S_d$	downward shortwave radiation flux	$\text{Wm}^{-2}$
$S_f$	stomatal resistance dependence on temperature	-
$S_g$	solar flux absorbed over bare ground	$\text{Wm}^{-2}$
$s_i$	soil water in layer i	-
$S_m$	rate of snow melt	$\text{kgm}^{-2}\text{s}^{-1}$
$SM$	soil moisture	mm
$S_{rw}$	rooting zone soil water	mm
$S_{rwmax}$	maximum rooting zone soil water	mm
$S_s$	clear air scattering of shortwave radiation flux	$\text{Wm}^{-2}$
$S_{sw}$	surface soil water (upper layer)	mm

$S_{swmax}$	maximum upper soil water	mm
$S_{tw}$	total water in the soil	mm
$S_{twmax}$	maximum water in total soil column	mm
$s_w$	soil water for which transpiration essentially goes to zero	-
$t$	time	s
$T$	Temperature	K
$T_a$	air temperature of lowest model layer	K
$T_{af}$	temperature within the foliage layer	K
$T_c$	cloud water transmissivity	-
$T_f$	temperature of foliage	K
$T_{g1}$	surface soil temperature	K
$T_{g2}$	subsurface temperature	K
$T_{g3}$	deep soil temperature	K
$T_p$	precipitation transmissivity	-
$T_v$	water vapour transmissivity	-
$u$	cross front wind velocity	$\text{ms}^{-1}$
$U$	horizontal wind speed; also effective rainfall	$\text{ms}^{-1}$ ; mm
$\bar{u}$	mean wind speed	$\text{ms}^{-1}$
$u_*$	surface frictional velocity scale	$\text{ms}^{-1}$
$U_a$	horizontal wind above the canopy	$\text{ms}^{-1}$
$U_{af}$	wind velocity within foliage layer	$\text{ms}^{-1}$
$u_c$	cloud water path	$\text{gm}^{-2}$
$u_g$	geostrophic wind	$\text{ms}^{-1}$
$u_p$	effective water path	$\text{gm}^{-2}$
$v$	along front wind velocity	$\text{ms}^{-1}$
$V_f$	fall speed of rain or snow ( $\text{ms}^{-1}$ ); also stomatal resistance dependence on vapour pressure deficit	-
$V_q$	relative volume of flow that travels through as quickflow	-
$V_s$	relative volume of flow that travels through as slowflow	-
$w$	vertically integrated cloud water path length; also a weighting function for the lateral boundary conditions	$\text{gm}^{-2}$

$W_{dew}$	total water stored by canopy per unit land area	$\text{mm m}^{-2}$
$W_{DMAX}$	maximum water the canopy can hold	$\text{mm m}^{-2}$
$W_{LT}$	soil dryness (or plant wilting) factor	-
$w_s$	mixed layer velocity scale	-
$x^{(q)}$	quickflow	mm
$x^{(s)}$	slowflow	mm
$z$	height above the surface	m
$z_0$	originating level of downdraft; also the roughness length	m
$z_l$	height of lowest model level	m
$z_b$	originating level of updraft	m
$Z_r$	depth of soil rooting layer	m



## *List of Acronyms*

<i>Acronyms</i>	<i>Meaning</i>
ABRACOS	Anglo-Brazilian Climate Observation Study
AMIP	Atmospheric Model Intercomparison Project
ARI	Average Recurrence Interval
ARPE	Average Relative Parameter Error
ASCE	American Society of Civil Engineers
BALTEX	Baltic Sea Experiment
BATS	Biosphere-Atmosphere Transfer Scheme
BOREAS	Boreal Ecosystem-Atmosphere Study
CMD	Catchment Moisture Deficit
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ECMWF	European Centre for Medium Range Weather Forecasts
EF	Evaporative Fraction
EFEDA	ECHIVAL Field Experiment in Desertification threatened Areas
ET	evapotranspiration
FIFE	First ISLSCP Field Experiment
GARP	Global Atmospheric Research Program
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratories
GISS	Goddard Institute for Space Studies
GMT	Greenwich Mean Time
HAPEX	Hydrological and Atmospheric Pilot Experiment
HEIFE	Hei Ho River basin Field Experiment
IFC	Intensive Field Campaign

IHACRES	Identification of Hydrographs And Components from Rainfall, Evaporation and Streamflow data
IPCC	Intergovernmental Panel on Climate Change
ISLSCP	International Satellite Land Surface Climatology Project
IUH	Instantaneous Unit Hydrograph
LAM	Limited Area (climate) Model
LTER	Long Term Ecological Reserve
MM5	Penn State/NCAR Mesoscale Model version 5
MOBILHY	Modelisation du Bilan Hydrique
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research, USA
NCEP	National Center for Environmental Prediction, USA.
NOAA	National Oceanic and Atmospheric Administration
NOPEX	Northern Hemisphere Climate Processes Land Surface Experiment
NSE	Nash-Sutcliffe Efficiency
PAM	Portable Automatic Mesonet stations
PBL	Planetary Boundary Layer
PET	Potential evapotranspiration
PILPS	Project for Intercomparison of Land-surface Parameterisation Schemes
PIRCS	Project to Intercompare Regional Climate Models
RegCM2	NCAR Regional Climate Model version 2
SHEELS	Simulator for Hydrology & Energy Exchange at the Land Surface
SRIV	Simple Refined Instrumental Variable technique
SVAT	Soil-Vegetation-Atmosphere Transfer scheme
UTC	Coordinated Universal Time (GMT)