

Index

- advective limit for ET, 75–76, 75*e*
- analytical probabilistic stormwater models (APSWM): conversion from exceedance probability to return period, 351–352; derived probability distribution theory, 342–343; flood control analysis, 354–360, 355*t*, 356*f*–358*f*, 359*t*; overview, 336–338; rainfall characterization, 338–340; rainfall event characteristics, 339–340, 339*t*; rainfall-runoff transformation, 340–341; runoff event peak discharge rate, 343–345; runoff event volume, 343; runoff routing through channel reaches, 348–351; runoff routing through detention ponds, 345–348, 346*f*
- annual extremes for different durations, 24*t*–25*t*, 24–26, 26*f*, 50–51, 69*f*–70*f*
- APSWM. *see* analytical probabilistic stormwater models
- aquifers. *see* groundwater hydrology
- Archimedean copulas, 420–421, 422*f*, 422*t*
- ARMA modeling: low flow analysis, 290–294; streamflow analysis, 210–212
- ASCE Standardized Reference ET Equation (ASCE05), 102, 102*e*
- Atlas 14 (NOAA), 29, 29*f*
- atmospheric evaporative demand (E_0): complementarity with ET, 81–83, 82*f*, 129–133; concept of, 71–73; drivers and limits, 74–78, 125–129; evaporation paradox and, 133–134; as limit to ET, 78–79; measurement of, 73–74; models of, 78–101; observations, 96–101; physics of, 73–78; temperature-based formulations, 93–95, 94*f*; trend decomposition, 130–132, 131*f*; trends, 124–129
- autocorrelation: evapotranspiration, 117–120, 118*f*, 119*f*; low flows, 288–299; soil properties, 162–163; streamflow time series, 204, 205*f*
- automated sampling, 400
- autoregressive moving average (ARMA) models: low flow analysis, 290–294; streamflow, 210–212
- Back Creek, West Virginia, flood frequency analysis, 252–255, 253*t*, 254*t*, 255*f*
- basin water balance estimates for ET, 83–85, 83*e*–84*e*, 91
- Baton Rouge, Louisiana, storm duration and depth analysis, 460–461, 462*f*–463*f*, 462*t*, 463–465, 464*t*, 465*f*–466*f*, 467, 468*f*–474*f*, 473, 475*t*–477*t*
- Bayesian methods, 234
- best management practices (BMP) for pollutant removal, 360–374, 361*t*–364*t*, 362*f*–363*f*, 367*f*–370*f*, 371*t*–372*t*, 374*f*
- beta distribution, 388–389
- binomial distribution, 389–390
- bivariate exponential distribution, 414–415, 415*f*
- bivariate extreme value type I distribution, 415–416, 417*f*
- bivariate log-normal distribution, 413–414
- bivariate normal distribution, 412–413, 413*f*
- bootstrap sampling, 46–49, 47*f*, 48*e*, 48*f*
- box-and-whisker plots, 393–394, 393*f*, 396
- Budyko framework for ET, 79–81, 80*e*–81*e*, 80*f*
- Bulletin 13, Methods of Flow Frequency Analysis (IACWR 1966), 235
- Bulletin 15, A Uniform Technique for Determining Flood Flow Frequencies (WRC 1967), 235
- Bulletin 17B, Guidelines for Determining Flood Flow Frequency (IACWD 1982), 234–236, 246–247, 249–252, 257
- Bulletin 17C, Guidelines for Determining Flood Flow Frequency (IACWD), 255–257
- capillary pressure head, 150, 150*f*
- CDFs. *see* cumulative distribution functions
- censored water quality data, 394–396
- channel reaches, 348–351
- Chicago, Illinois, flood control analysis, 354–360, 355*t*, 356*f*–358*f*, 359*t*
- chi-squared test, 193–194, 194*t*, 195*f*

- climate change: flood frequency analysis and, 257–261; low flows and drought and, 325; precipitation frequency analysis and, 51–52
- coefficient of skew: defined, 183, 183e; gamma PDF, 187; log-gamma PDF, 189; log-normal PDF, 185
- coefficient of variation: gamma PDF, 187; log-gamma PDF, 189; log-normal PDF, 185
- complementarity of regional ET and E_0 , 81–83, 82f, 129–133, 131f, 132t
- complex river system modeling, 222–228
- conditional probability adjustment (CPA), 250, 253
- copulas: analytical goodness-of-fit tests, 441–443, 443t–444t, 458–460, 459t–460t, 461f, 467, 473, 475t–477t, 479, 481, 484t; Archimedean, 420–421, 422f, 422t; assessment of fitting, 449, 451, 458–460, 465, 467, 473, 478–479, 481; concept of, 417f, 418; dependence and, 424–436; dependence structure and test space, 446f–448f, 447–448, 461, 463, 463f, 474, 477, 480f; derivation of associated copulas, 424; error statistics of fit, 440–441, 441t, 451, 458, 458t, 467, 475t, 479, 481, 483t; estimation of dependence parameter, 431–436, 448–449, 449t, 464–465, 464t, 477, 480t; exact maximum likelihood method of estimation, 435–436; extreme value, 421, 423; graphical goodness-of-fit methods, 437–438, 438f–441f, 440, 449, 450f–457f, 451, 465, 465f–466f, 467, 468f–474f, 478–479, 481f–483f; invariance property, 424–425; maximum pseudo-likelihood method of estimation, 435; meta-elliptic, 423; miscellaneous, 423–424; moment-like method of estimation, 431, 433–435; nonparametric measures of association, 425–427, 427t; overview, 416–418; peak flow and volume analysis, 444–449, 445f–448f, 449t, 450f–458f, 451, 458–460, 458t–460t, 461f; potential marginal distributions, 445–447, 446f; qualitative assessment of dependence, 427–429, 428f, 430f; random number generation and, 436; regional flood risk analysis, 473–474, 478–479, 478t, 480t, 481–485, 483t–484t; selection process, 436–443, 437f; storm duration and depth analysis, 460–461, 462f–463f, 462t, 463–465, 464t, 465f–466f, 467, 468f–474f, 473, 475t–477t; tail dependence characteristics, 429–431, 432t, 433f–434f; types of, 418–424
- correlation coefficient, 181, 181e
- correlation scale, 181
- CPA (conditional probability adjustment), 250, 253
- crop ET (ET_c). *see* reference crop ET
- cumulative distribution functions (CDFs): copulas, 418, 419f; empirical frequency analysis and, 273–274, 273e, 395; precipitation frequency analysis, 10–11, 11t, 34f
- cumulative probability plots, 10–11, 69f–70f
- daily precipitation time series, 22–23, 22f–23f
- dam effects on low flows, 321–323
- Darcy's Law, 150, 150e
- DARMA modeling: drought length, 302; low flows, 293–294
- decision making aids for infiltration and soil water processes, 172
- derived distribution method, uncertainty analysis, 364
- derived probability distributions: runoff characteristics, 342–354; runoff event peak discharge rate, 343–345; runoff event volume, 343; runoff routing through channel reaches, 348–351; runoff routing through detention ponds, 345–348, 346f; theory, 342–343
- descriptive indexes for precipitation extremes, 53–54, 53t
- deseasonalization, 213–214, 213e–214e
- design storms, 336–337
- detention ponds: flood control analysis, 354–360, 355t, 356f–358f, 359t; runoff routing, 345–348, 346f
- dimensionless relationships in infiltration, 160–162, 161f
- dimming, 126–128
- disaggregation models, 224–228
- discrete ARMA modeling: drought length, 302; low flows, 293–294
- diversion effects on low flows, 321–323
- droughts: climate change and, 325; DARMA modeling, 302; defined, 272, 273f; intensity, 305–307, 320; length, 300–305, 303t, 304f, 305t; magnitude, 305–308, 310–312, 320; overview, 2–3, 269–270; probability distributions, 300–308, 310–316; regional analysis, 319–321; return period,

316–319, 319f; statistical characterization, 299–319

duration: of drought, 272, 273f; of low flow, 271, 271f; of storm, 460–461, 462f–463f, 462t, 463–465, 464t, 465f–466f, 467, 468f–474f, 473, 475t–477t

Durbin-Watson test, 40, 40e

E_0 . *see* atmospheric evaporative demand

eddy covariance technique, 85–88, 85e, 87e

effective saturation, 150, 150e, 150f

El Niño southern oscillation (ENSO), 257–261, 260t, 261t, 262f

EMA. *see* expected moments algorithm

EML (exact maximum likelihood) method, 435–436

empirical analysis: low flows, 273–274; precipitation frequency analysis, 10–11; water quality variables, 395

energy balance modeling, 88–93, 89f, 92f, 93f

ENSO (El Niño southern oscillation), 257–261, 260t, 261t, 262f

enteric bacteria, spring water quality modeling, 198–200, 200f

envelope curves. *see* flood envelope curves

E_{pan} . *see* pan evaporation

EQRM (equi-ratio quantile matching), 36–37, 36f, 37e

ET. *see* evapotranspiration

ET_c (crop ET). *see* reference crop ET

ETCDI (Expert Team on Climate Change Detection and Indexes), 53–54, 53t (ET^{WB}). *see* water balance-derived ET

evaporation. *see* evapotranspiration (ET)

evaporation paradox, 133–134

evapotranspiration (ET): advective limit, 73–74, 73e; atmospheric evaporative demand (*see* atmospheric evaporative demand); autocorrelation, 117–120, 118f, 119f; Budyko framework, 79–81, 80e–81e, 80f; complementarity with E_0 , 81–83, 82f, 129–133; defined, 71; dimming and, 126–128; drivers and limits, 74–78, 125–129, 132–133, 132t; eddy covariance estimation, 85–88, 85e, 86f, 87e; energy and water limits, 79–81; energy balance modeling, 88–93, 89f, 92f, 93f; estimation of, 72; evaporation paradox and, 133–134; GCM modeling and, 122; global observations, 121–122; Mann-Kendall test, 117–120, 119f; measurement of, 73–74;

models, 78–101; moisture availability limit, 74–75, 74e; overview, 2; Penman-Monteith approach, 101–102, 102e; physics of, 73–78; radiative driver, 76–78, 76e–77e, 76f; reference crop ET (*see* reference crop ET); regional trends across CONUS, 123–125, 123f; remote sensing and, 88–93, 89f, 92f, 93f; stilling and, 128–129; trend analysis, 116–134; utilization of concept, 71–72; water balance estimates, 83–85, 83e–84e, 91

exact maximum likelihood (EML) method, 435–436

exceedance probability of envelope curves, 516–522, 519f, 521f, 522t

expected moments algorithm (EMA), 252, 253–255, 254t, 255f, 256–257, 263–264

expected value: gamma PDF, 186; log-gamma PDF, 188; log-normal PDF, 184

Expert Team on Climate Change Detection and Indexes (ETCDI), 53–54

exponential distribution: bivariate, 414–415, 415f; groundwater hydrology, 186; hydraulic conductivity data, 195–196, 196t; precipitation data, 13; record events, 495t, 500

extreme events: droughts (*see* droughts); floods (*see* flood frequency analysis); precipitation (*see* precipitation extremes); record events (*see* record events)

extreme value copulas, 421, 423

extreme value type I distribution: hydrologic analysis, 415–416, 417f; precipitation extremes, 12; record events, 495t, 496–498, 497f

extreme value type III distribution: low flow frequency analysis, 279–280, 280f; precipitation data, 12; water quality variables, 388–389

FARMA (fractionally differenced autoregressive moving average) models, 218–220

FDCs (flow duration curves), 321–322, 324f

first-order gamma-autoregressive modeling, 291–295, 295f, 295t

first-order second moment, uncertainty analysis, 364–365

flood control. *see* urban stormwater management

flood envelope curves: basic formula, 509, 509e; empirical, 519–522, 521f, 522t; exceedance probability, 516–522, 519f, 521f, 522t;

- historical background, 508*f*, 509, 510*t*, 511;
overview, 508–509; probabilistic
interpretation of, 513–519, 514*f*, 522–526,
523*f*, 524*t*, 525*f*, 526*t*, 527*f*–528*f*;
relationships, 511–512, 512*f*, 513*f*; theory of
records and, 515–516, 515*f*; traditional
applications, 509, 511
- flood frequency analysis: annual flood series
model, 240–243; block adjustment, 257–258;
case studies of record events, 522–532;
copula-based analysis, 473–474, 478–479,
478*t*, 480*t*, 481–485, 483*t*–484*t*; envelope
curves (*see* flood envelope curves); estimation
procedures, 245–257; expected moments
algorithm, 252, 253–255, 254*t*, 255*f*, 256–257,
263–264; historical information and, 250–252,
251*f*, 256–257, 262; log-Pearson type III
distribution and, 234, 236–238, 240–244; low
outliers, 249–250, 252–253, 256, 262; method
of moments (MOM), 245–248; moments of
number of record events, 503–504, 505*t*;
multivariate distributions, 410–412, 504–508,
506*t*; nonparametric properties of record
events, 501–508; overview, 2, 233–234;
parametric adjustment, 257–258; parametric
properties of record events, 494–501;
parametric relationships, 258–259; probability
distribution of number of record events, 503,
504*f*; recommendations under development,
255–257; record theory and, 491–533;
recurrence time for record event, 501–502,
502*e*; regional risk analysis, 473–474, 478–479,
478*t*, 480*t*, 481–485, 483*t*–484*t*; runoff routing
through channel reaches, 348–351; theory of
records and, 526–531, 529*f*–531*f*, 531*t*; waiting
time for record event, 501–502, 502*e*
- Florida: annual precipitation extreme, example,
24*t*–25*t*, 24–26, 26*f*; climate cycles and
rainfall, 51–52, 52*f*; intensity-duration-
frequency curve for rainfall, 26–28, 27*f*
flow duration curves (FDCs), 321–322, 324*f*
FLUXNET, 85, 86*f*
- fractional Gaussian noise model, 217–218
- fractionally differenced autoregressive moving
average (FARMA) models, 218–220
- frequency analysis: of floods (*see* flood
frequency analysis); of low flows, 273–274
- frequency distributions, 28–29, 29*f*
- frequency factors, 18–19
- gamma distribution: drought magnitude, 307,
309*t*–310*t*; groundwater hydrology, 185–188;
precipitation data, 13; residence time and age
of groundwater, 196–198, 197*f*; spring water
quality modeling, 198–200, 200*f*; water
quality variables, 388–389
- Gauley subbasin, West Virginia, regional flood
risk analysis, 473–474, 478–479, 478*t*, 480*t*,
481–485, 483*t*–484*t*
- Gaussian distribution. *see* normal distribution
- general circulation model (GCM) simulations:
evapotranspiration and, 122; precipitation
extremes and, 56
- generalized extreme value (GEV) distribution:
low flow series, 280–282, 281*f*; precipitation
data, 13; record events, 495*t*, 498–500, 499*f*
- generalized Pareto distribution, 495*t*, 500–501
- geometric mean, 182, 182*e*
- geostatistical scaling methods, 162–163, 163*f*,
164*f*
- Geum River basin, Korea, low flow analysis,
322, 323*f*
- GEV distribution. *see* generalized extreme value
distribution
- glossaries: record events, 491–492; water quality
variables, 381–383
- goodness-of-fit tests: annual extremes for
different durations, 24*t*–25*t*, 24–26, 26*f*;
copula selection, 437–438, 438*f*–441*f*,
440–443, 443*t*–444*t*, 449, 450*f*–457*f*, 451,
458–460, 459*t*–460*t*, 461*f*, 465, 465*f*–466*f*,
467, 468*f*–474*f*, 473, 475*t*–477*t*, 478–479, 481,
481*f*–483*f*, 484*t*; daily precipitation time
series, 22–23, 22*f*–23*f*; hydraulic conductivity
data, 193–194, 194*t*, 195*f*; L-moment
diagrams, 21; normal distributions, 20;
quantitative measures, 21
- gravity drainage, 152
- Greenbrier River, West Virginia, peak flow and
volume analysis, 444–449, 445*f*–448*f*, 449*t*,
450*f*–458*f*, 451, 458–460, 458*t*–460*t*, 461*f*
- Greenbrier subbasin, West Virginia, regional
flood risk analysis, 473–474, 478–479, 478*t*,
480*t*, 481–485, 483*t*–484*t*
- green building design principles, 352–354
- ground-based measurements of precipitation,
6–7
- groundwater hydrology: coefficient of skew,
183, 183*e*; geometric mean, 182, 182*e*;

- notations for aquifer properties, 182;
- overview, 2; probability density functions, 183–190; probability distributions, 179–201; residence time and age, 196–198, 197f; sample average, 182, 182e; spring water quality modeling, 198–200, 200f; standard deviation, 182–183, 182e–183e; statistical definitions, 180–181; variance, 182
- Guidelines for Determining Flood Flow Frequency, Bulletin 17 series (IACWD), 234–236, 246–247, 249–252, 255–257
- Gumbel distribution. *see* extreme value type I distribution
- Han River basin, Korea, low flows analysis, 322, 323f–325f
- historical information: flood frequency analysis and, 250–252, 251f, 256–257, 262; precipitation frequency analysis and, 31–32
- homogeneity: E_{pan} data, 99–101; precipitation extremes, 42–44; statistical, 181
- homogeneous region selection for low flow analysis, 284–285
- Hortonian overland flow, 151
- Hurst effect, 162, 207–208, 217–221
- hydraulic conductivity: aquifers, 179, 180f; exponential PDF application, 195–196, 196t; infiltration and, 150–151; log-gamma PDF application, 192–194, 193f, 194t, 195f; log-normal PDF application, 191–192, 191f–192f; temporal variability, 158–160; vertical soil heterogeneity, 156
- HYDRO-35, 28–29
- hydrologic analysis: bivariate exponential distribution, 414–415, 415f; bivariate extreme value type I distribution, 415–416, 417f; bivariate log-normal distribution, 413–414; bivariate normal distribution, 412–413, 413f; copula method, 416–443 (*see also* copulas); flood events, 410–412; hydrometeorological applications, 408–410; multivariate distributions, 408–416; overview, 3, 407–408
- hydrologic cycle: evapotranspiration (*see* evapotranspiration); floods (*see* flood frequency analysis); groundwater (*see* groundwater hydrology); infiltration (*see* infiltration); multivariate frequency distributions in (*see* hydrologic analysis); precipitation extremes (*see* precipitation extremes); record events (*see* record events); soil water (*see* soil water); stormwater management and (*see* urban stormwater management); streamflow (*see* streamflow)
- hydrologic design: future data sources, 52–53; future of, 57
- hypergeometric distribution, 390
- IDF (intensity-duration-frequency) curves: precipitation extremes, 26–28, 27f
- IDWM (inverse distance weighting method), 32–33
- IETD (interevent time definition), 51
- IHA (Indicator of Hydrologic Alteration), 321–322, 322t
- impervious areas, 340, 341
- independence: defined, 181; evaluation of, 49–50
- Indicator of Hydrologic Alteration (IHA), 321–322, 322t
- infilling methods, 34–35, 34f
- infiltrability. *see* infiltration capacity (f_c)
- infiltration: acronyms and symbols, 172–173; approximation techniques, 153; boundary and initial conditions, 152; capillary pressure head, 150, 150f; cumulative, 151; decision support systems, 172; dimensionless relationships, 160–162, 161f; dynamics of, 151–153; effective parameters of heterogeneous soil, 163–165; effective saturation, 150, 150e, 150f; engineering treatment of, 148; geostatistical scaling, 162–163, 163f, 164f; Hortonian overland flow, 151; hydraulic conductivity and, 150–151; hydrologic process interactions, 145–147, 146f, 148f; local measurement uncertainty, 166–167; local processes, 150–151; numerical solution methods, 152–153; overview, 2; parameter estimation, 167; pedotransfer functions and, 160, 161f; plant canopy and, 148–149, 149f; quantification challenges, 170–171; Richard's Equation, 151, 151e; runoff and, 168–170; scaling and estimation, 160–165; soil-surface sealing and, 153–154; soil-water content measurement, 154, 155f; sorptivity, 156; space-time simulations, 168–172; spatial variability, 156–158, 158f, 159f, 159t; surface flux measurements, 154–156; temporal variability, 158–160; uncertainty, 147, 166–168; variability, 147, 156–160; vertical soil heterogeneity and, 156;

- water transfer process, 150–151; wetting process, 150–151
- infiltration capacity (f_c), 146–147, 151, 160–162, 161*f*
- intensity-duration-frequency (IDF) curves, 26–28, 27*f*
- interevent time definition (IETD), 51, 338
- intermittent flows, 216–217, 282–283, 283*f*
- interpolation methods, 32–37, 34*f*
- invariance property of copulas, 424–425
- inverse distance weighting method (IDWM), 32–33
- inverse methods, 167
- joint probability distributions: drought characteristics, 312–316; regional flood risk analysis, 481–485, 484*f*–485*f*
- Kaplan Meier approach, 395
- k-C* model, 360–371, 361*t*–364*t*, 362*f*–363*f*, 367*f*–370*f*
- kernal density estimation (KDE), 46, 46*e*
- k-nearest neighbors resampling (KNNR), 221–222
- LAI (leaf area index), 148–149
- land surface temperature, 93–95, 94*f*
- Las Palmas Creek, California, spring water quality, 198–200, 200*f*
- Latin hypercube sampling, uncertainty analysis, 365
- leaf area index (LAI), 148–149
- LFCs (load frequency curves), 372–373, 374*f*
- linear regression, 39–42
- Little River, North Carolina, flood frequency analysis, 247–248, 248*t*, 249*f*
- Ljung-Box Q test, 40–42, 41*e*
- L-moment analysis: flood frequency analysis, 243–244, 244*f*, 244*t*; precipitation data, 17–18, 21
- load frequency curves (LFCs), 372–373, 374*f*
- log-gamma distribution. *see* log-Pearson type III distribution
- log-normal distribution: bivariate, 413–414; groundwater hydrology, 183–185; hydraulic conductivity data, 191–192, 191*f*–192*f*; low flow series, 276–278, 278*f*, 278*t*; precipitation data, 12, 12*e*; water quality variables, 387–388
- log-Pearson type III distribution: annual flood series model, 240–243, 242*f*; characteristics of, 236–244; defined, 13, 237–238, 237*e*, 239*f*, 240*t*; flood frequency analysis and, 234, 255–256; groundwater hydrology, 188–190; hydraulic conductivity data, 192–194, 193*f*, 194*t*, 195*f*; L-moments, 243–244, 244*f*, 244*t*; log space characteristics, 236, 240–241; low flow series, 274–276, 276*t*; real space characteristics, 237–238, 241–242
- log space method of moments, 245–248
- long memory models, 218–220
- Los Angeles, California, BMP performance for pollutant removal, 371–374, 371*t*–372*t*, 374*f*
- low flows: ARMA modeling, 290–294; autocorrelated flow analysis, 288–299; climate change and, 325; DARMA modeling, 293–294; defined, 270–272, 271*f*; empirical frequency analysis, 273–274; extreme value type III distribution, 279–280, 280*f*; first-order gamma-autoregressive modeling, 291–295, 294*t*, 295*f*; fitting of univariate distributions, 274–282; generalized extreme value distribution, 280–282, 281*f*; hydraulic structures and, 321–323, 322*t*, 323*f*–325*f*; intermittent flows, 282–283, 283*f*; log-Pearson type III distribution, 274–276, 276*t*; overview, 2–3, 269–270; probability distribution, 274–283; regional analysis, 283–288 (*see also* regional analysis of low flows); return period and risk, 295–299, 298*f*, 298*t*–299*t*; simple Markov chain modeling, 288–290, 289*f*; three-parameter log-normal distribution, 276–278, 278*f*, 278*t*
- low-impact development practices, 352–354
- LP3 distribution. *see* log-Pearson type III distribution
- MADI (mean absolute deviation index), 21
- Mann-Kendall test: evapotranspiration, 117–120, 119*f*; precipitation extremes, 38–39, 38*e*–39*e*, 41*f*
- Mann-Whitney U statistic, 43, 43*e*
- Mapocho River, Chile, low flow analysis, 294–295, 294*t*, 295*f*
- maximum likelihood estimation method, 17
- maximum pseudo-likelihood (MPL) method, 435
- mean absolute deviation index (MADI), 21
- mean square deviation index (MSDI), 21
- measurements: censored water quality data, 394–396; evapotranspiration, 73–74;

- infiltration, 166–168, 171; precipitation, 6–9; soil-water content, 154, 155*f*; 166–168, 171; statistical homogeneity and independence, 181; surface flux, 154–156
- median: gamma PDF, 186; log-gamma PDF, 189; log-normal PDF, 184
- meta-elliptic copulas, 423
- method of moments (MOM): copula dependence parameters, 431–435, 448–449, 449*t*, 464–465, 464*t*; flood frequency analysis, 245–248; precipitation extremes, 16–17; reference crop ET, 106–115, 108*f*–114*f*; with regional skew, 246–248
- Methods of Flow Frequency Analysis, Bulletin 13 (IACWR 1966), 235
- MGBT (multiple Grubbs-Beck outlier test), 256–257
- mode: gamma PDF, 187; log-gamma PDF, 189; log-normal PDF, 184
- model process uncertainty, 167
- moisture availability limit for ET, 74–75, 74*e*
- moments: detection of changes, 44–45, 45*t*; of distributions, 19*t*; drought length, 300–305; estimation of distribution parameters, 17–18; expected moments algorithm, 252, 253–255, 254*t*, 255*f*, 256–257, 263–264; first-order second moment, uncertainty analysis, 364–365; gamma PDF, 187; L-moments approach (*see* L-moment analysis); log-gamma PDF, 189–190; method of moments, 16–17; number of record events, 503–504, 505*t*; record event analysis, 496
- MPL (maximum pseudo-likelihood) method, 435
- MSDI (mean square deviation index), 21
- multinomial distribution, 391
- multiple Grubbs-Beck outlier test (MGBT), 256–257
- multivariate analysis: hydrological variables, 407–485 (*see also* hydrologic analysis); record events, 504–508, 506*t*; time series modeling, 223–224; water quality variables, 401–402
- negative binomial distribution, 391
- New River, Virginia, flood risk forecast, 259–261, 260*t*, 261*t*, 262*f*
- NEXt Generation RADar (NEXRAD), 7–8, 8*f*
- Niger River, 220, 220*e*
- NLDAS (North American Land Data Assimilation System), 106–108
- nonparametric methods: bootstrap sampling, 46–49, 47*f*, 48*e*, 48*f*; copulas and, 425–427, 427*t*; estimation of quantiles and proportions, 391–393; independence evaluation, 49–50; kernel density estimation, 46, 46*e*; precipitation extremes, 45–50; ranked von Neumann test, 50, 50*e*; record event analysis, 501–508; runs test, 48–50, 49*e*–50*e*; streamflow modeling, 221–222; water quality variables, 391–394
- normal distribution: bivariate, 412–413, 413*f*; goodness-of-fit tests, 20; precipitation data, 12, 12*e*; water quality variables, 358–386
- normality testing of water quality, 386–387
- North American Land Data Assimilation System (NLDAS), 106–108
- North Central Italy, probabilistic regional envelope curves, 523–524, 523*f*, 524*t*
- outliers in flood frequency analysis, 249–250, 252–253, 256, 262
- pan evaporation (E_{pan}). *see* E_{pan} : decomposition of trends, 129–130; derivation of E_0 , 94–96; evaporation paradox and, 133–134; observed E_0 , 96–97; trend analysis and, 116, 124–125; uncertainty and limitations, 97–101
- Paraná River, Argentina, low flow return period and risk, 297–299, 298*f*, 298*t*–299*t*
- PARMA streamflow models, 214–216
- partial duration series, 50–51
- PDFs. *see* probability density functions
- Pearson type III distribution: defined, 236, 236*e*, 237*f*; precipitation data, 13
- pedotransfer functions (PTFs), 160, 161*f*
- Penman-Monteith approach to ET, 101–102, 102*e*
- Penns Creek, Pennsylvania, low flow estimation, 275–276, 276*t*
- performance modeling for BMP pollutant removal: description of k-C* model, 360–364; k-C* model, 361*t*–364*t*, 362*f*–363*f*; load frequency curve approach, 372–373, 374*f*; overview, 360; sensitivity, 365–371, 367*f*–370*f*; uncertainty, 361–363, 365–374
- periodic autoregressive moving average (PARMA) models, 214–216
- periodicity of streamflows, 206, 206*f*
- pervious areas, 341

- Philip's infiltration equation, 153, 153e, 157, 158t
- physics of evapotranspiration, 73–78
- PILFs (potentially influential low floods), 256
- plant canopy interception of rainfall, 148–149, 149f
- PMP (probable maximum precipitation), 30–31
- Poisson distribution, 338–339, 390–391
- ponding time, 151, 152, 152f
- population of interest, defining, 396–397
- porosity of common rocks, 179, 180t
- potentially influential low floods (PILFs), 256
- Poudre River, Colorado: drought intensity analysis, 306–307; drought length analysis, 302–305, 303t, 304f, 305t; drought magnitude analysis, 306–307; drought return period analysis, 317–319, 319f; streamflow variability analysis, 208–209, 208f–209f
- precipitation extremes: annual extremes for different durations, 24t–25t, 24–26, 26f, 50–51, 69f–70f; bootstrap sampling, 46–49, 47f, 48e, 48f; changes in moments, 44–45, 45t; characterization of data, 11–13, 14t–16t; copula-based analysis, 460–461, 462f–463f, 462t, 463–465, 464t, 465f–466f, 467, 468f–474f, 473, 475t–477t; cumulative distribution functions, 10–11; daily precipitation time series, 24, 24f, 25f; descriptive indexes, 53–54, 53t; distribution parameter estimation, 19–20; droughts (*see* droughts); E_{pan} errors, 98–99; errors in measurement, 6; estimation, 7–9; frequency factors, 18–19; GCM simulations, 56; goodness-of-fit tests, 20–26; ground-based measurement, 6–7; homogeneity, 42–44; independence evaluation, 49–50; interevent time definition, 51; kernel density estimation, 46, 46e; linear regression, 39–42; Mann-Kendall test, 38–39, 38e–39e, 41f; Mann-Whitney U statistic, 43, 43e; measurement, 5–9; monitoring networks, 6–7; nonparametric methods, 45–50; overview, 1, 5; parametric frequency curves, 26–28, 27f; partial duration series, 50–51; precipitation frequency analysis (*see* precipitation frequency analysis); probability distributions, 9–13; probable maximum precipitation, 30–31; quantile mapping, 35–37, 36f, 37e; radar-based measurements, 7–9, 52–53; ranked von Nuemann test, 50; as record events, 492; regional envelope curves, 525–526, 525f, 526t, 527f–528f; regional frequency analysis, 21–22; runs test, 48–50, 49e–50e; satellite-based measurement, 9; Spearman's rank correlation coefficient (ρ) test, 37–38, 37e, 39, 40f; standard precipitation index, 54–56, 54e–55e; stationarity issues, 37–42; storm duration and depth analysis, 460–461, 462f–463f, 462t, 463–465, 464t, 465f–466f, 467, 468f–474f, 473, 475t–477t
- precipitation frequency analysis: annual extreme value series, 50–51; climate change and, 51–52; cumulative distribution functions, 10–11, 11t; estimation in, 32–35; future data sources, 52–53; GCM simulations, 56; length of historical data, 31–32; missing data, 32–36, 34f, 36f; regional, 21–22; sample adjustment factors, 31; uncertainty and variability, 31–37; for United States, 28–29, 29f
- preferential flow, 167
- principal component analysis, 401–402
- probability density functions (PDFs). *see also specific probability distributions*: defined, 180–181; groundwater hydrology, 183–190; maximum likelihood estimation method, 17; precipitation data, 11–13; standard precipitation index, 54–56, 54e–55e
- probability distributions. *see also specific probability distributions*: annual precipitation extreme, example, 24t–25t; characterization of precipitation data, 11–13, 14t–16t; derived, 342–354; drought characteristics, 300–316; drought intensity, 305–307; drought length, 300–305; drought magnitude, 305–308, 309t–310t, 310–312; evaluation of residuals, 41t; flood frequency analysis, 233–234; frequency factors, 18–19; goodness-of-fit tests, 20–26; in groundwater hydrology, 179–201; moments, 17–18, 19t, 21; number of record events, 503, 504f; overview, 11; parameter estimation, 16–18; precipitation extremes, 9–10, 13; record theory and, 493–494; stormwater modeling, 336–338; water quality variables, 384–403
- probability sampling: serial correlation and, 399; water quality variables, 397
- probability-weighted moments (PWM), 17–18
- probable maximum precipitation (PMP), 30–31

- proportions, nonparametric estimation, 392–393
- ProUCL, 387
- PTFs (pedotransfer functions), 160, 161*f*
- PWM (probability-weighted moments), 17–18
- quantile mapping, 35–37, 36*f*, 37*e*
- quantiles: censored data, 396; log-gamma PDF, 190; log-normal PDF, 185, 187–188; nonparametric estimation, 391–393; record event analysis, 496
- radar-based measurements of precipitation, 7–9, 8*f*
- radiative driver for ET, 76–78, 76*f*, 126–128
- rainfall: characterization of local conditions, 338–340; conversion from exceedance probability to return period, 351–352; droughts (*see* droughts); extremes (*see* precipitation extremes); frequency analysis (*see* precipitation frequency analysis); infiltration (*see* infiltration); multivariate distributions, 408–410; probabilistic models, 339–340, 339*t*; runoff generation, 340–341; separation of events, 338–339; water harvesting storage unit sizing, 352–354
- rain gauges, 6–7
- random number generation, 436
- ranked von Neumann test, 50, 50*e*
- record events: case studies, 522–532; definitions, 491–492; exponential distribution, 495*t*, 500; extreme value type I distribution, 495*t*, 496–498, 497*f*; flood envelope curves (*see* flood envelope curves); generalized extreme value distribution, 495*t*, 498–500, 499*f*; generalized Pareto distribution, 495*t*, 500–501; moments of number of events, 503–504, 505*t*; multivariate distributions, 504–508, 506*t*; nonparametric properties, 501–508; overview, 3; parametric properties, 494–501; probability distribution of number of events, 503, 504*f*; properties of United States floods, 526–531, 529*f*–531*f*, 531*t*; recurrence time, 501–502, 502*e*; theory of, 492–494; waiting time, 501–502, 502*e*
- recurrence time for record event, 501–502, 502*e*
- reference crop ET (ET_{rc}): approach, 79; ASCE05, 102, 102*e*; concept of, 71–72, 101; derivation of crop ET from reference ET, 102–103; method of moments variability analysis, 106–115, 108*f*–114*f*; Penman-Monteith approach to ET, 101–102, 102*e*; sensitivity analysis, 104–106, 105*f*; uncertainty, 103–104
- regional analysis of droughts, 319–321
- regional analysis of low flows: baseflow correlation, 286–288; homogeneous region selection, 284–285; overview, 283; regression model, 285–286
- regional envelope curves, 513–519, 514*f*, 522–526, 523*f*, 524*t*, 525*f*, 526*t*, 527*f*–528*f*
- regional frequency analysis of precipitation extremes, 21–22
- regression models, 285–286
- regression on order statistics (ROS), 395
- remote sensing: energy balance modeling of ET and, 88–93, 89*f*, 92*f*, 93*f*; soil-water content, 171
- reservoirs, 207–209
- residence time and age of groundwater, 196–198, 197*f*
- return period: droughts, 316–319, 319*f*; low flows, 295–299, 298*f*, 298*t*–299*t*; urban stormwater management, 351–352
- Richard's Equation, 151, 151*e*
- risk assessment: infiltration and soil water processes, 172; low flows, 295–299, 298*f*, 298*t*–299*t*; regional flood risk analysis, 473–474, 478–479, 478*t*, 480*t*, 481–485, 483*t*–484*t*
- rivers: flood frequency (*see* flood frequency analysis); low flows (*see* low flows); record events (*see* record events); streamflow modeling (*see* streamflow); water quality (*see* water quality)
- ROS (regression on order statistics), 395
- runoff: derived probability distributions, 342–354; detention ponds and, 345–348; infiltration and, 168–170; overview, 3; peak discharge rate, 343–345; rainfall transformation, 340–341; routing through channel reaches, 348–351; saturation excess overland flow, 151; volume, 343
- run-on, 168
- runs test, 48–50, 49*e*–50*e*
- Salso River, Italy, drought magnitude analysis, 308, 310*t*, 311–312, 312*t*, 316–317
- sample adjustment factors, 31

- sample average, 182, 182*e*. *see also* expected value
- San Pedro River, Mexico, low flow estimation, 277–282, 278*f*, 278*t*, 280*f*, 281*f*
- satellite-based measurements of precipitation, 9
- saturated hydraulic conductivity, 150–151, 164–165, 165*f*, 168–170, 169*f*, 170*f*
- scaling, 160–165, 168–170
- seasonality: evapotranspiration, 125;
streamflow modeling, 213–216; streamflow time series, 204–206; water quality, 400–401
- SEEB (Simplified Surface Energy Balance)
modeling, 89*f*, 92*f*–93*f*
- sensitivity analysis: performance modeling of
pollutant removal, 365–371, 367*f*–370*f*;
reference crop ET, 104–106, 105*f*
- serial correlation: automated sampling and, 400;
nearly continuous monitoring and, 400;
probability sampling and, 399; stochastic processes, 399; trend analysis and, 399–400;
water quality, 398–400
- shifting mean models, 220–221
- simple Markov chain, 288–290, 289*f*
- Simplified Surface Energy Balance (SSEB)
modeling, 88–93, 89*f*, 92*f*–93*f*
- snowfall. *see* precipitation extremes
- software: infiltration and soil water processes, 172; streamflow modeling, 228; water quality data, 387, 389
- soil properties: effective parameters of
heterogeneous soil, 163–165; infiltration and, 148; pedotransfer functions and, 160, 161*f*;
scaling of, 160–165; soil-surface sealing, 153–154; surface flux measurements, 154–156; temporal variability, 158–160; water content measurement, 154, 155*f*
- soil water. *see also* infiltration: acronyms and symbols, 172–173; hydrologic process interactions, 145–147, 146*f*, 147*f*; local processes, 150–151; measurement methods, 154, 155*f*, 166–168, 171; space-time simulations, 168–172; spatial variability, 156–158, 158*f*, 158*t*, 159*f*, 159*t*; temporal variability, 158–160; uncertainty, 147, 166–168; variability, 147, 156–160
- sorptivity, 156
- spatial correlation, 181
- spatial interpolation methods, 32–37, 36*f*
- spatial variability of infiltration, 156–158, 158*f*, 158*t*, 159*f*, 159*t*
- Spearman's rank correlation coefficient (ρ) test, 37–38, 37*e*, 39, 40*f*
- spring water quality modeling, 198–200, 200*f*
- SSEB (Simplified Surface Energy Balance)
modeling, 88–93
- standard deviation, 182–183, 182*e*–183*e*
- standard precipitation index, 54–56, 54*e*–55*e*
- stationarity, 37
- statistical analysis. *see also specific statistical methods*: droughts, 299–319;
evapotranspiration, 71–135; precipitation extremes, 5–57
- statistical homogeneity, 181
- statistical inference: aquifer properties, 182–183; infiltration and soil water, 167–168
- stilling, 128–129
- stochastic modeling: serial correlation and, 399;
streamflow variability, 203–229; water quality data, 397–398
- storm events. *see* precipitation extremes
- stormwater management. *see* urban stormwater management
- streamflow: ARMA models, 210–212;
autocorrelation, 204; complex river system modeling, 222–228; copula-based analysis, 444–449, 445*f*–448*f*, 449*t*, 450*f*–458*f*, 451, 458–460, 458*t*–460*t*, 461*f*; defined, 203;
deseasonalization, 213–214, 213*e*–214*e*;
disaggregation models, 224–228; flow regime, 321–322; fractional Gaussian noise model, 217–218; Hurst effect, 207–208; intermittent flow models, 216–217; long memory models, 218–220; long-term variability models, 217–221; low flows (*see* low flows); modeling strategies for complex river systems, 226–228; multivariate time series modeling, 223–224; nonparametric modeling, 221–222; overview, 2; peak flow and volume analysis, 444–449, 445*f*–448*f*, 449*t*, 450*f*–458*f*, 451, 458–460, 458*t*–460*t*, 461*f*; periodic models, 214–216; product models for intermittent flows, 216–217; seasonality, 204–206; seasonal series modeling, 213–216; shifting mean models, 220–221; software tools, 228; stochastic features, 203–209; stochastic modeling, 209–222; storage-related statistics, 207–209; variability modeling, 203–229; water quality and, 400–401
- surface energy balance modeling of ET, 88–93, 89*f*, 92*f*, 93*f*

- surface flux measurements, 154–156
- surface infiltration. *see* infiltration
- surface seal, 153–154
- symbols: infiltration and soil water, 172–173; urban stormwater management, 333–335
- Technical Paper (TP) 40, 28–29
- temperature-based formulations of E_0 , 93–95, 94f
- temporal variability of soil properties, 158–160
- tension infiltrometer methods, 155
- three-parameter log-normal distribution: low flow series, 276–278, 278f, 278t; precipitation data, 12
- time series for streamflow: autocorrelation, 204, 205f; Hurst effect, 207–208; modeling, 209–222; seasonality, 204–206; stochastic features, 203–209; storage-related statistics, 207–209
- time series for water quality, 397–398
- TP-40, 28–29
- transformations of water quality data, 386–387
- trend analysis: evapotranspiration, 116–134; precipitation extremes, 37–42, 42f; serial correlation and, 399–400
- Tropical Rainfall Measuring Mission (TRMM), 9
- t-tests, 44–45
- Twelve Mile Creek, North Carolina, low flow estimation, 283, 283f
- Tyrol, Austria, probabilistic regional envelope curves, 525–526, 525f, 526t, 527f–528f
- uncertainty. *see also* variability: analysis methods, 364–365; derived distribution method, 364; evapotranspiration, 72; first-order second moment, 364–365; infiltration and soil water, 147, 166–168; k-C* model and, 361–363; Latin hypercube sampling, 365; pollutant removal BMP performance modeling, 361–363, 365–374; precipitation frequency analysis, 31–37; reference crop ET (ET_{rc}), 103–104; sensitivity, 365–370, 367f–370f
- Uniform Technique for Determining Flood Flow Frequencies, Bulletin 15 (WRC 1967), 235
- United States: flood frequency analysis, 233–264 (*see also* flood frequency analysis); precipitation frequency analysis, 28–29, 29f; record-breaking floods, 526–531, 529f–531f, 531t
- universal multifractal models, 168–170, 169f, 170f
- Upper Colorado River basin, disaggregation models, 227–228
- urban stormwater management: analytical probabilistic models, 336–360; conversion from exceedance probability to return period, 351–352; derived probability distributions for runoff characteristics, 342–354; flood control analysis, 354–360, 355t, 356f–358f, 359t; overview, 3; pollutant removal performance modeling, 360–374, 361t–364t, 362f–363f, 367f–370f, 371t, 372f; rainfall characterization, 338–340; rainfall-runoff transformation, 340–341; runoff event peak discharge rate, 343–345; runoff event volume, 343; runoff routing through channel reaches, 348–351; runoff routing through detention ponds, 345–348, 346f; symbols, 333–335
- variability. *see also* uncertainty: infiltration and soil water, 147; precipitation frequency analysis, 31–37; reference crop ET, 106–115, 108f–114f
- variance: defined, 182; gamma PDF, 187; log-gamma PDF, 189; log-normal PDF, 185
- von Neumann's ratio test, 50, 50e
- waiting time for record event, 501–502, 502e
- Wald-Wolfowitz test, 48–50, 49e–50e
- water balance-derived ET (ET^{WB}), 83–85, 83e–84e, 91, 132–134, 132t
- water management. *see* urban stormwater management
- water pollution: BMP performance modeling, 360–374, 361t–364t, 362f–363f, 367f–370f, 371t–372t, 374f; microbiological contaminants, 390–391
- water quality: analysis of variables, 381–403; beta distribution, 388–389; binomial distribution, 389–390; box-and-whisker plots, 393–394, 393f; censored observations, 394–396; definitions, 381–383; extreme value type III distribution, 388–389; gamma distribution, 388–389; hypergeometric distribution, 390; log-normal distribution, 387–388; microbiological variables, 390–391; multinomial distribution, 391; multivariate

- characterization, 401–402; negative binomial distribution, 391; nonparametric representations of data, 391–394; normal distribution, 358–386; normality testing of data, 386–387; overview, 3, 383; Poisson distribution, 390; population of interest, defining, 396–397; practical applications of distributions, 384–385; probability sampling, 397; seasonality, 400–401; serial correlation, 398–400; special characteristics of variables, 383–384; springs, 198–200, 200*f*; stochastic processes, 397–398; streamflow and, 400–401; time series, 397–398; transformation of data, 386–387
- Water Resources Council (WRC), 235
- Water Resources Planning Act, 235
- water table, infiltration and, 152
- Watson, Keith, 157
- Weather Surveillance Radar 88-Doppler (WSR 88-D), 7–8, 8*f*
- Weibull distribution. *see* extreme value type III distribution
- WRC (Water Resources Council), 235
- WSR 88-D (Weather Surveillance Radar 88-Doppler), 7–8, 8*f*
- Z-statistic. *see* Mann-Kendall test