

Progress in Stochastic Analysis, Modeling, and Simulation: SAMS-2003

O.G. B. Sveinsson¹, J.D. Salas², W.L. Lane³, and D.K. Frevert⁴

¹Post-Doctoral Fellow, International Research Institute (IRI), Columbia University, N. York (formerly graduate student at Colorado State University, Fort Collins, Colorado).

²Professor of Civil Engineering, Colorado State University, Fort Collins, Colorado 80523 (on sabbatical leave at the Institute of Hydromechanics and Water Resources Management, ETH, Zurich, Switzerland)

³Private Consultant, Golden, Colorado 80401 (formerly at the U.S. Bureau of Reclamation, Denver, Colorado).

⁴Hydraulic Engineer, U.S. Bureau of Reclamation, Technical Services Center, Lakewood, Colorado 80225

Abstract. SAMS is a software for stochastic analysis, modeling, and simulation of hydrologic time series such as streamflows. It has been written in MS Visual C++ and Fortran. The package consists of many menu option windows that focus on three primary application modules - Statistical Analysis of Data, Fitting of a Stochastic Model (including parameter estimation and testing), and Generating Synthetic Series. SAMS has the capability of analyzing single site and multisite annual and seasonal data such as monthly and weekly streamflows based on a number of single site and multisite models, and aggregation and disaggregation modeling schemes. Results can be presented in graphical and tabular forms and, if desired, saved to an output file. The purpose of the paper is to summarize and update on the current capabilities of SAMS. Some illustrations are made to demonstrate the improved technical capabilities of the program using flow data of the Colorado River system.

1. Introduction

Stochastic hydrology has been a technology available to many water organizations for several decades. For instance, the U.S. Army Corps of Engineers (USACE, 1971) developed the HEC-4 model which has been widely used for extension and generation of monthly hydrologic data such as streamflows. Likewise, the U.S. Bureau of Reclamation developed the LAST (Lane Applied Stochastic Techniques) stochastic hydrology package in the late 1970's for the purpose of modeling and simulation of streamflows for multi-site stream network systems (Lane, 1978; Lane and Frevert, 1990). Typical applications of stochastic analysis and simulation include reservoir capacity determination, reservoir yield analysis, low flow and drought analysis, evaluating operating rules of reservoir systems, performance evaluation of hydraulic structures under uncertain streamflows, irrigation system evaluation under uncertain water deliveries, and water resources impact analysis of climate change (Salas et al, 1980; Loucks et al, 1981; Salas, 1993; Hipel and McLeod, 1994).

Despite of the availability of general-purpose statistical software such as S-Plus, SAS/ETS, SPSS, MINITAB, STATVIEW, IMSL, and MATLAB, etc., specialized software for frequency analysis of extreme hydrologic events such as extreme precipitation and extreme floods, and software for simulation of hydrologic time series such as annual and monthly streamflows, have been attractive in the field because of several reasons (Salas et al, 2003). Firstly,

hydrologic time series may require stochastic models that may not be readily available in standard statistical packages such as models with long memory, and models that may be capable of producing shifting patterns such as those that are observed in certain hydrometeorological processes. Secondly, the periodic nature of hydrological processes, such as monthly and weekly streamflows, require periodic stochastic models or models with periodically varying parameters. Lastly, many of the stochastic models and simulation schemes that are useful for complex hydrologic and water resources systems, such as models for temporal and spatial disaggregation, have been developed specifically to fit the needs of water resources. In addition to HEC-4 and LAST as noted above, SPIGOT (Grygier and Stedinger, 1990) and more recently, SAMS (Salas et al, 2002) are specific software packages developed for multisite hydrologic simulation. The latter software SAMS, which stands for Stochastic Analysis, Modeling and Simulation, has been developed in collaboration between Colorado State University and the U.S. Bureau of Reclamation (Salas et al, 2003).

The main purpose of this paper is to summarize the capabilities of SAMS-2003 and to illustrate some of them by using a case study. First, a brief summary of the key concepts utilized in stochastic simulation is made followed by another section that summarizes the current features of SAMS-2003. Subsequently, some of the capabilities of SAMS are illustrated using data of the Colorado River System.

2. Stochastic Simulation

Stochastic simulation of hydrologic time series is generally conducted using mathematical models. These models commonly require analyzing the temporal and spatial variability of the series under consideration. For example, first and second order statistics such as the mean, variance, and covariance are useful in any type of statistical analysis. Higher order moments such as skewness, and some other statistics related to surplus, drought, and storage are of interest from the practical standpoint. Furthermore, most of the stochastic models available for simulation assume that the underlying variable is normally distributed, an assumption that is not generally met by most hydrologic data. Thus it is commonly necessary to test the hypothesis that the original data are normally distributed and to transform them into normal if the hypothesis is rejected.

A number of stochastic models have been suggested in literature for stochastic simulation of hydrologic processes such as streamflow (e.g. Salas, 1993; Hipel and McLeod, 1994). One of the most popular and simplest models is the autoregressive model denoted as $AR(p)$ as shown in Table 1. This model has been widely utilized for stochastic simulation of hydrologic and water resources data. Choosing a type of model for the data at hand depends on several factors such as, physical and statistical features of the process under consideration, complexity of the system, purpose of the study, experience, and often the availability of specialized software (Salas et al, 1980). Furthermore, for complex water resources systems, “modeling schemes”, which are

assembly of several models linked in certain ways depending on the system's configuration, the number of sites, and the objective of the study is generally needed (Salas et al, 1980; Grygier and Stedinger, 1990). Once the stochastic model and modeling scheme have been defined for the system at hand, the next step is to estimate the model parameters. This can be accomplished based on the method of moments or maximum likelihood depending on the model and modeling scheme. The model(s) are then tested using certain goodness of fit and evaluation criteria to judge whether they comply with the underlying assumptions of the model and whether they are capable of producing statistical features and hydrologic events that are important for the problem at hand (e.g. Salas et al., 1980; Loucks et al, 1981; Salas, 1993; Hipel and MacLeod, 1994). Finally, based on the selected stochastic model, simulations (data generation) are performed for the intended objective (e.g. evaluating the performance of a reservoir built for supplying supplemental water to an irrigation system). Figure 1 briefly summarizes the various steps as noted above.

Table 1. Example of a Stochastic Model Commonly Used for Simulation Studies

$$x_t = \mu + \sum_{j=1}^p \phi_j (x_{t-j} - \mu) + \varepsilon_t$$

$$\hat{\mu} = \bar{x}$$

$$\hat{\phi}_1 = r_1 \quad (\text{for } p = 1)$$

$$\hat{\sigma}_\varepsilon^2 = s^2(1 - r^2) \quad (\text{for } p = 1)$$

where:

\bar{x} = sample mean

s^2 = sample variance

r_1 = sample lag-1 serial correlation coefficient

$\hat{\sigma}_\varepsilon^2$ = noise variance

3. Capabilities of SAMS-2003

SAMS-2003 has been written in C++ and Fortran and runs under modern windows operating systems such as WINDOWS 2000. Its menu allows the user to choose between numerous analytical options, particularly (a) Stochastic Analysis of Data, (b) Fitting a Stochastic Model, and (c) Generating Synthetic Series. Some key features of SAMS-2003 are summarized in Table 2.

A key concept in SAMS is that of temporal and spatial disaggregation (downscaling). Spatial disaggregation relies on the concept of key stations,

substations, subsequent stations, and further “upstream” stations. In some cases, the key stations may be the farthest downstream stations, substations are the next stations upstream, subsequent stations are next further upstream stations, and so on. SAMS has the capability of unlimited sequence of stations. Three schemes are available for modeling the data of the key stations and upstream stations as summarized in Table 2. In Schemes 1 and 2 annual generation is conducted first, and subsequently the annual quantities are temporally disaggregated into seasonal. In Scheme 3 seasonal quantities are first

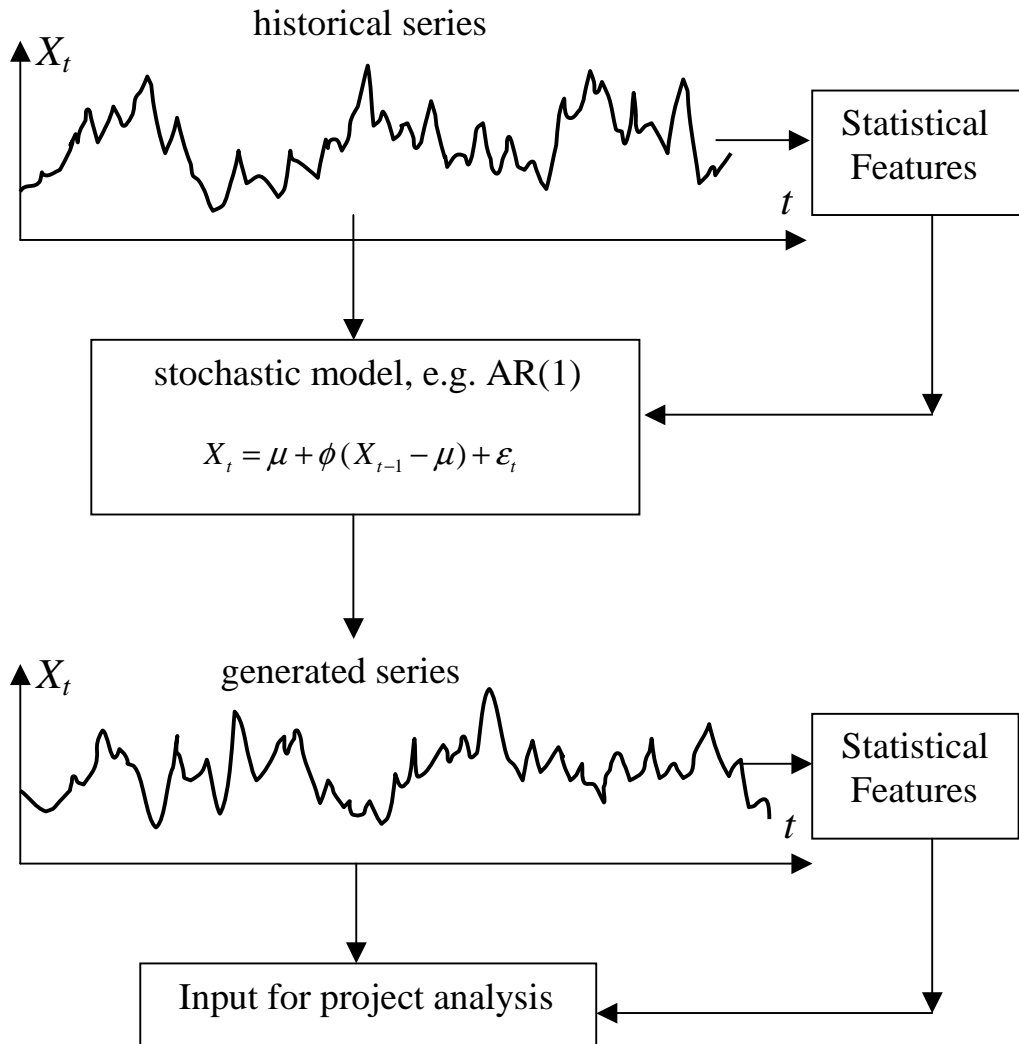


Figure 1. Schematic of stochastic generation using an AR(1) model built from the historical series. Simulations are performed that provide a wide range of possible flow traces that may occur in the future. They also useful for testing project design and management alternatives.

Table 2. Main features currently available in SAMS-2003

Main Functions	Temporal Scale	Features
Stochastic Analysis	Annual	<ul style="list-style-type: none"> • Basic 1st and 2nd order statistics and skewness • Drought related statistics • Surplus related statistics • Storage related statistics • Data transformations
	Seasonal	Same as above
	Sub-seasonal (e.g. weekly)	Same as above
	Daily	Same as above
Stochastic Modeling	Annual	Single site: AR(p), ARMA(p,q), GAR(1), SM* Multisite: MAR, CARMA, CSM*, CSM-CARMA* Spatial disaggregation: VS, MR
	Seasonal	Single site: PAR(p), PARMA(p,q) Multisite: MPAR(p) Scheme 1: <ul style="list-style-type: none"> - Univariate generation, annual at index-station - Spatial disaggregation, annual at index station to annual at key stations - Multivariate disaggregation, annual at key stations to annual at substations - Multivariate disaggregation, annual at substations to annual at further upstream stations, etc. - Multivariate disaggregation of annual to seasonal at any group of stations Scheme 2: <ul style="list-style-type: none"> - Multivariate generation, annual at key stations - Then the same steps as above Scheme 3*: (Grygier-Stedinger's method) <ul style="list-style-type: none"> - Multivariate generation, annual at key stations - Multivariate disaggregation, annual to seasonal at key stations - Multivariate spatial disaggregation, seasonal at key stations to seasonal at substations - Multivariate spatial disaggregation, seasonal at substations to further upstream stations.
	Sub-seasonal (e.g. weekly)	Not currently available except in one step.
	Daily	Not currently available
Stochastic Simulation	Annual	Available for any models/schemes as specified above
	Seasonal	Available for any models/schemes as specified above
	Sub-seasonal (e.g. weekly)	Not currently available
	Daily	Not currently available
* To become available by June 2003		

generated at key stations, then they are spatially disaggregated (into seasonal quantities) at other upstream stations. If seasonal data (e.g. monthly) are desired in Schemes 1 and 2, temporal disaggregation models are fitted to disaggregate the annual values at desired stations into seasonal values. Seasonal time scales may be monthly, weekly, quarter-monthly or any desired partitions of the calendar year. Current temporal disaggregation models are not recommended for use with time periods shorter than weekly. In the near future, plans are in place for the addition of models appropriate for a second level of temporal disaggregation that will allow the generation of sub-seasonal quantities (e.g. quarter-monthly or weekly after a previous temporal disaggregation from annual to monthly) or daily values. Furthermore, spatial and temporal disaggregation models can be fitted to all stations at once (one group containing all the stations) or to stations arranged in various groups.

In summary, SAMS-2003 statistically analyzes and transforms the input data as needed, fits models based on any of the various options available, and generates synthetic hydrologic data. The statistical characteristics of the observed and generated data and the generated samples are presented in graphical or tabular forms and printed or written on special output files and they can be copied into Excel.

Case Example

A brief illustration is presented herein to demonstrate some of the capabilities of SAMS 2003 using the data of the Upper Colorado River system. Stochastic data bases had been generated for the Colorado in the 1980's using the LAST program (Lane and Frevert, 1990). The Colorado River is one of the important river systems of the United States and one of the most important sources of water supply for seven western states including Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada, and California. Its basin includes parts of these seven states and the Republic of Mexico. The waters of the Colorado are utilized for irrigation, municipal, hydropower, industrial, mining, recreational and environmental purposes. The Colorado River system has been subject to a number of adverse climatic episodes ranging from wet periods to periods of drought (US Bureau of Reclamation, 1986 and Fulp and Harkins, 2001). Historically observed streamflow data show periods of high flows such as those that formed the basis of the 1922 Colorado River Compact and also the very high flow years of 1982-83 and 1983-84. On the other hand, the record also shows periods of drought such as the dust bowl years of the late 1920s and 1930s and also the mid 1950s. While the current state of the art does not allow accurate long-range prediction of these climatic extremes, the stochastic approach to hydrologic data can offer managers a better understanding and appreciation of the types of streamflow extremes they may face in the future.

For this example, we utilized 85 years of historically observed monthly data at 16 sites in the basin (Fig.2). Prior to using SAMS, the data at some sites have been extended in order to make them cover the same period at all sites. Likewise, the data have been "naturalized" in order to remove from the measured flow data the effect of regulation or diversions. We analyzed both

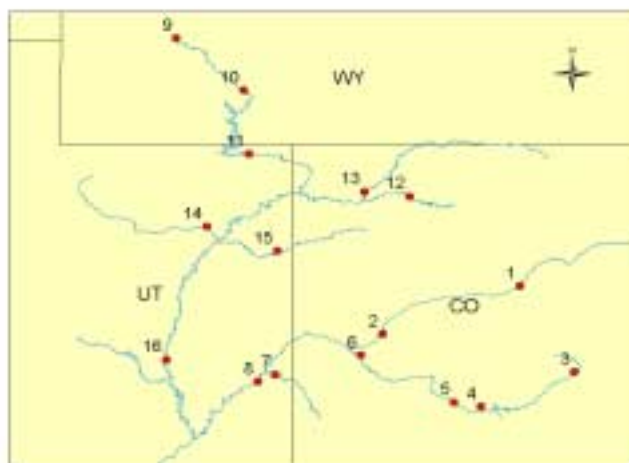


Figure 2. Schematic of the streamflow network for 16 sites of the Upper Colorado River System.

the annual and the monthly streamflow series. Figure 3 shows the table of the input file monthly data for the 16 sites. SAMS has been used to determine basic annual statistics (mean, standard deviation, skewness, auto-correlations and cross-correlations) as well as storage and drought related statistics in both the original and transformed (into normally distributed flows) domains. Also for the monthly series monthly statistics have been determined such as, monthly means, standard deviations, skewness coefficients, and month-to-month correlations and cross-correlations. For illustration Fig. 4 shows the correlogram of the annual flows for site 16 while Fig. 5 shows the month-to-month cross-correlations for sites 8 and 16. Figure 6 illustrates the results obtained for transforming the June flows (season 6) for site 16 using a logarithmic transformation. It shows the distribution of annual flows in the original and lognormal domains using a normal probability paper.

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1 station: 000710 COLORADO RIVER NEAR S.D.MARSH SPRINGS CO
2 station: 000801 COLORADO RIVER ABOVE CANON CO
3 station: 000901 YELLOW RIVER ABOVE TAYLOR FORK RES CO
4 station: 001001 GARRISON RIVER ABOVE GOLD MEADOW DAM CO
5 station: 001101 GARRISON RIVER ABOVE CAPITAL DAM CO
6 station: 001201 GARRISON RIVER ABOVE GRAND SECTION
7 station: 001301 GOLFERS RIVER NEAR CIRCLE UT
8 station: 001401 COLORADO RIVER ABOVE CIRCLE UT
9 station: 001501 GREEN RIVER BELOW FORTWENTY FIVE MI WY
10 station: 001601 GREEN RIVER ABOVE GREEN RIVER MI
11 station: 001701 GREEN RIVER ABOVE GREENWALD LP
12 station: 001801 YUMPA RIVER NEAR WYBULL CO
13 station: 001901 LITTLE SHOSHONE RIVER NEAR LITTLE CO
14 station: 002001 SAGEHEN RIVER NEAR BARKLEY UT
15 station: 002101 WHITE RIVER NEAR SECTION UT
16 station: 002201 GREEN RIVER ABOVE GREEN RIVER UT

Number of sites: 16
Year of data: 11
Seasonal: 12

Station: 1
Year: 1980
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071 2072 2073 2074 2075 2076 2077 2078 2079 2080 2081 2082 2083 2084 2085 2086 2087 2088 2089 2090 2091 2092 2093 2094 2095 2096 2097 2098 2099 2100 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2123 2124 2125 2126 2127 2128 2129 2130 2131 2132 2133 2134 2135 2136 2137 2138 2139 2140 2141 2142 2143 2144 2145 2146 2147 2148 2149 2150 2151 2152 2153 2154 2155 2156 2157 2158 2159 2160 2161 2162 2163 2164 2165 2166 2167 2168 2169 2170 2171 2172 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2183 2184 2185 2186 2187 2188 2189 2190 2191 2192 2193 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2205 2206 2207 2208 2209 2210 2211 2212 2213 2214 2215 2216 2217 2218 2219 2220 2221 2222 2223 2224 2225 2226 2227 2228 2229 2230 2231 2232 2233 2234 2235 2236 2237 2238 2239 2240 2241 2242 2243 2244 2245 2246 2247 2248 2249 2250 2251 2252 2253 2254 2255 2256 2257 2258 2259 2260 2261 2262 2263 2264 2265 2266 2267 2268 2269 2270 2271 2272 2273 2274 2275 2276 2277 2278 2279 2280 2281 2282 2283 2284 2285 2286 2287 2288 2289 2290 2291 2292 2293 2294 2295 2296 2297 2298 2299 2300 2301 2302 2303 2304 2305 2306 2307 2308 2309 2310 2311 2312 2313 2314 2315 2316 2317 2318 2319 2320 2321 2322 2323 2324 2325 2326 2327 2328 2329 2330 2331 2332 2333 2334 2335 2336 2337 2338 2339 2340 2341 2342 2343 2344 2345 2346 2347 2348 2349 2350 2351 2352 2353 2354 2355 2356 2357 2358 2359 2360 2361 2362 2363 2364 2365 2366 2367 2368 2369 2370 2371 2372 2373 2374 2375 2376 2377 2378 2379 2380 2381 2382 2383 2384 2385 2386 2387 2388 2389 2390 2391 2392 2393 2394 2395 2396 2397 2398 2399 2400 2401 2402 2403 2404 2405 2406 2407 2408 2409 2410 2411 2412 2413 2414 2415 2416 2417 2418 2419 2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 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2781 2782 2783 2784 2785 2786 2787 2788 2789 2790 2791 2792 2793 2794 2795 2796 2797 2798 2799 2800 2801 2802 2803 2804 2805 2806 2807 2808 2809 2810 2811 2812 2813 2814 2815 2816 2817 2818 2819 2820 2821 2822 2823 2824 2825 2826 2827 2828 2829 2830 2831 2832 2833 2834 2835 2836 2837 2838 2839 2840 2841 2842 2843 2844 2845 2846 2847 2848 2849 2850 2851 2852 2853 2854 2855 2856 2857 2858 2859 2860 2861 2862 2863 2864 2865 2866 2867 2868 2869 2870 2871 2872 2873 2874 2875 2876 2877 2878 2879 2880 2881 2882 2883 2884 2885 2886 2887 2888 2889 2890 2891 2892 2893 2894 2895 2896 2897 2898 2899 2900 2901 2902 2903 2904 2905 2906 2907 2908 2909 2910 2911 2912 2913 2914 2915 2916 2917 2918 2919 2920 2921 2922 2923 2924 2925 2926 2927 2928 2929 2930 2931 2932 2933 2934 2935 2936 2937 2938 2939 2940 2941 2942 2943 2944 2945 2946 2947 2948 2949 2950 2951 2952 2953 2954 2955 2956 2957 2958 2959 2960 2961 2962 2963 2964 2965 2966 2967 2968 2969 2970 2971 2972 2973 2974 2975 2976 2977 2978 2979 2980 2981 2982 2983 2984 2985 2986 2987 2988 2989 2990 2991 2992 2993 2994 2995 2996 2997 2998 2999 3000
    
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Figure 3. Input file of the monthly streamflow data for the 16-site network

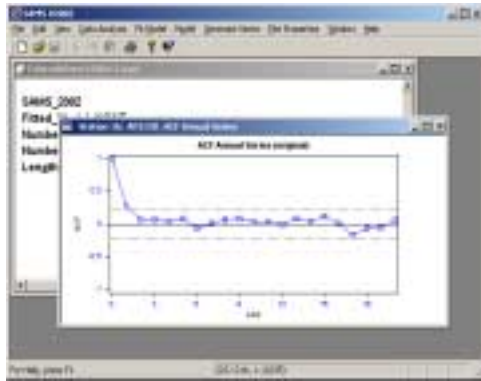


Figure 4. Correlogram of the annual flows for site 16.

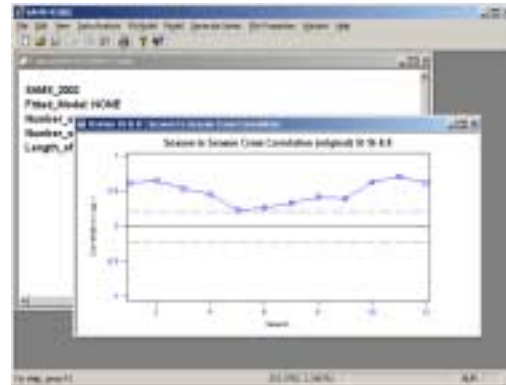


Figure 5. Month-to-month crosscorrelations for sites 8 and 16.

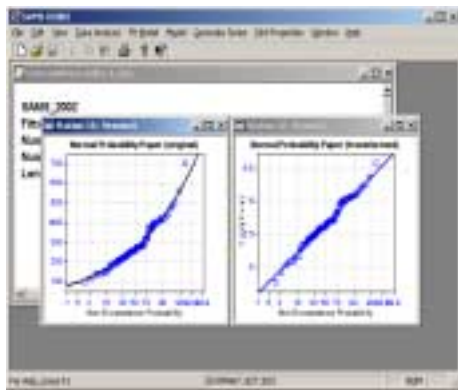


Figure 6. Distribution of June flows for site 16 using logarithmic transformation.

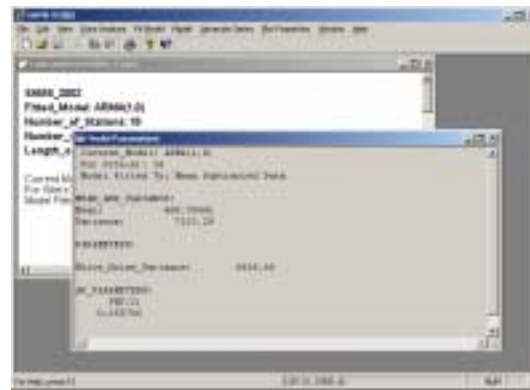


Figure 7. ARMA(1,0) parameters for the annual log-transformed flows for site 16.

Figure 7 displays results of fitting the ARMA(1,0) model to the annual log-transformed flows for site 16. The mean and the variance (i.e. $\bar{x} = 408.8$, $s^2 = 7133.3$) of the underlying log-transformed annual flows and the model parameters: $\hat{\phi}_1 = 0.256$ and $\hat{\sigma}_\varepsilon^2 = 6666.7$ are shown. Figure 8 displays a table of results comparing some historical and generated statistics using the referred AR(1) model. The generated statistics are actually the average of the statistics obtained from a specified number of simulated samples. Then, Fig.9 is a comparison of the historical sample and a generated sample of the same length as the historical. Figures 10-14 illustrate the case in which 16 stations (1 through 16) were utilized for modeling the monthly flows of the 16-site system. We selected the modeling scheme 2 as shown in Fig.10. This figure also shows that the Valencia-Schaake model was selected for the spatial disaggregation. Figure 11 shows the window menu where stations 8 and 16 are selected as the key stations and the MAR(2) (multivariate autoregressive model of order 2) model is used for fitting both sites jointly. Fig. 12 shows that sites 1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15 (actually the last three number are not shown in the figure) will be the substations that correspond to

the key sites 8 and 16. They are put together into a single group for fitting a spatial disaggregation model to disaggregate the annual flows of sites 8 and 16 into the annual flows for the other 14 sites as Fig. 13 shows. Then Fig. 14 shows that two groups of stations (1, 2, 3, 4, 5, 6, 7, 8) and (9, 10, 11, 12, 13, 14, 15, 16) were selected for the temporal model, i.e. to disaggregate the annual flows into the monthly flows.

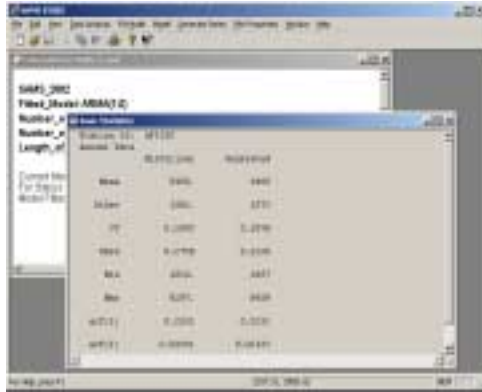


Figure 8. Comparison of historical and generated basic statistics for annual flows (site 16)

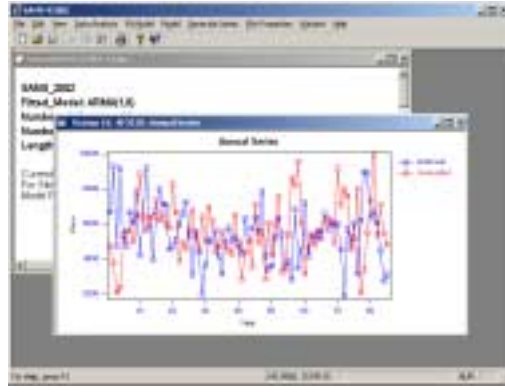


Figure 9. Comparison of historical and generated annual flows for site 16.

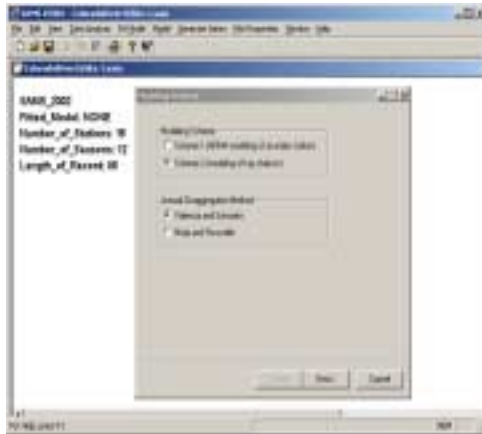


Figure 10. Window menu for selecting a modeling scheme and spatial disaggregation.

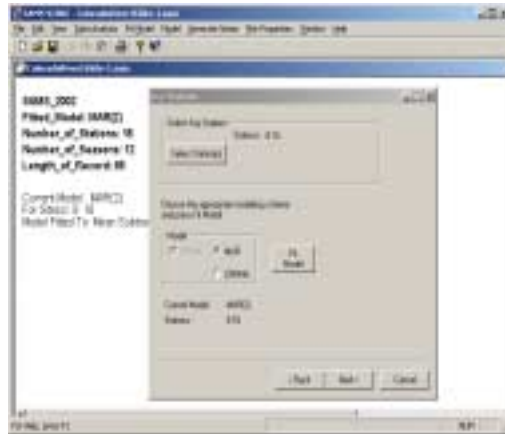


Figure 11. Sites 8 and 16 are the selected key sites and MAR(2) model is the chosen model.



Figure 12. Selection of substations belonging to sites 8 and 16.

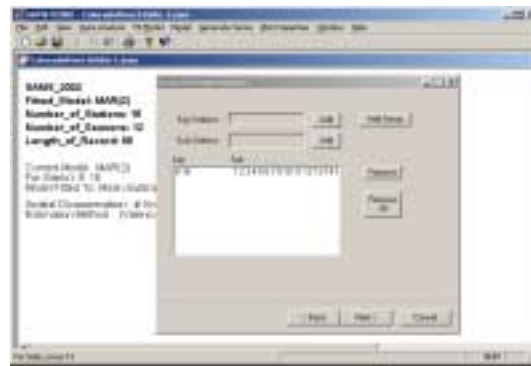


Figure 13. The key sites 8 and 16 and the substations 1, 2, 3, etc. are put into one group.

Finally, Fig. 15 shows the window menu utilized for selecting options for data generation. The generation is performed based on the model specification (including data transformations and standardizations as the case may be) determined previously. For illustration the model is ARMA(0,0) for site 16, the length of the generated series is 85 years, and the number of samples to generate is 100. In addition, the menu indicates that the generated data will be saved (on a file).

Data generated by SAMS on the Colorado River is being utilized in long term studies of the Colorado for both Bureau of Reclamation and its clients. These studies required development of a set of data management interfaces between SAMS and the RiverWare modeling framework developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado (Zagona, et al, 2001) and the Hydrologic Data Base used by Reclamation for management of the Colorado River basin. Results of such analysis integrating both modeling frameworks will be described elsewhere.



Figure 14. Temporal disaggregation will be made for the two groups of stations as shown.



Figure 15. Windows menu for selection of options for data generation.

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Sveinsson, also a former CSU graduate student. The technical effort to utilize the stochastic data base in RiverWare on the Colorado River Basin has been strongly supported by Dr. T. Fulp of the Bureau of Reclamation's Lower Colorado Regional Office, by Mr. D. King of the Bureau of Reclamation's Technical Service Center and by Dr. E. Zagona and Mr. J. Prairie of the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES).

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