Cherry Creek Reservoir Watershed Model

Analysis of the Prediction of Total Runoff and Runoff Sources by the Cherry Creek Basin Authority Model

Prepared by: William M. Lewis, Jr.
James F. Saunders, III
Date of preparation: July 23, 2001
Minor revisions: January 25, 2002

R/146

Introduction

The Cherry Creek Basin Authority authorized and supported the preparation of a watershed model for Cherry Creek Reservoir in support of its nutrient control programs. Watershed models are common and appropriate tools in situations where eutrophication of a receiving water can be attributed, at least in part, to dispersed non-point sources, as is the case for Cherry Creek Reservoir. Watershed models take a variety of forms. The choice of a particular watershed model depends in part on the degree of documentation that is available in support of the model and the mix of nutrient sources that is expected for the watershed that is to be modeled.

The watershed model for Cherry Creek Basin was created by Brown and Caldwell Engineers for the Cherry Creek Basin Authority. It has two major components. The first component, which will here be referred to as the hydrologic component, gives predictions of the amount of water reaching the reservoir in any given year as a result of the amount and distribution of precipitation that year. The second component, which will be referred to here as the phosphorus loading component, estimates the total amount of phosphorus that is transported to the reservoir along with surface and subsurface flow for the hydrologic conditions in a particular year. The purpose of this report is to analyze and comment on the hydrologic component of the watershed model.

The watershed model created by Brown and Caldwell is an Excel spreadsheet that contains provisions for input conditions in a given year consisting of spatially explicit amounts of precipitation on a one-hour time scale. Information on precipitation is processed in such a way as to produce estimates of effective precipitation, i.e., precipitation that is capable of generating runoff. Equations are then used in predicting amount of runoff from amount of effective precipitation. Information on runoff from various sectors of the watershed is summed to produce an estimate of total runoff to the reservoir. Total runoff predicted by the model for a given year is checked against total runoff in the same year as estimated empirically by Chadwick Ecological Consultants on the basis of gaged surface flow and water level in wells, which is used in calculating subsurface flow. The empirical runoff information from Chadwick Ecological Consultants is adjusted to match (normalize to) the Army Corps of Engineers calculated inflow for Cherry Creek Reservoir prior to being used in any comparisons with modeled runoff. Thus, in effect, the total modeled runoff is being compared to the calculated inflow as determined by the Army Corps of Engineers.

A review of the runoff component of the watershed model must take into account the treatment of the input data and the manipulation of precipitation data to produce estimates of effective precipitation. In addition, a review must include the applicability or validity of assumptions that underlie the equations that give estimates of runoff, and the normalization process based on calculated inflow as derived from the Army Corps of Engineers. Each of these topics will be dealt with in this report.

Each of the topics mentioned above is analyzed on the basis of the watershed model software. Some documentation is included with the software, but the software itself was used as a primary source of information for this report. Because some intermediate steps used in developing the model are not evident from the software,

why didn't ? authors pursue this.

however, consultation with the authors of the model may help to clarify some of the points that remain unclear as of the date of preparation of this report.

Use of Raw Precipitation Data in Modelling

The authors of the model obtained hourly precipitation for five gages in the Cherry Creek watershed (Castle Rock, Cherry Creek Dam, Parker, Greenland 6, and Greenland 9). All hours in an annual record showing precipitation less than 0.1 inch per hour (the detection limit for hourly measurements) were treated as having zero precipitation. Hours for which there were no data also were treated as having zero precipitation.

Model
based on
Runoff
Producing
events

The assumption that precipitation is zero when the record shows less than 0.1 inch per hour or when no data are available introduces a bias because it excludes some precipitation. This bias could be trivial or it could be significant, and only a comparison with the empirically-observed annualized values can make this distinction. Table 1 shows the annual precipitation for the three gage locations as estimated by the procedures that were used in preparation of the watershed model. The table also shows the annual precipitation as obtained from daily gage readings, which are recorded separately for the hourly readings (source: Western Regional Climate Center). The table shows that the procedure used by the modelling team significantly underestimates mean precipitation by 10% at Castle Rock, 24% at Cherry Creek Dam, and 14% at Parker, and can be widely deviant from actual precipitation in some specific years, and that precipitation for some years is very poorly estimated.

☐- Check Data ?

Gage Year	Estimated for Modelling 100x inches/yr	Actual 100x inches/yr
Castle Rock		
1989	840	1443
1990	2070	1973
1991	940	- **
1992	1530	- **
1993	1540	1661
1994	1270	1555
1995	2120	1968
1996	1600	1447
1997	1630	2076
1998	1820	2042
Mean	1611	1770
Cherry Creek Dam		
1989	1040	1227
1990	690	1635
1991	1030	1703
1992	1470	1832
1993	1440	1552
1994	930	1049
1995	1810	2317 *
1996	1130	1483
1997	1860	2174
1998	1780	1885 *
Mean	1199	1582
Parker		
1989	1010	1156
1990	1580	1785
1991	1370	1699
1992	1400	1508
1993	1320	1523
1994	1150	1402
1995	1410	2017
1996	1190	1105
1997	1890	1893 *
1998	1916	- **
Mean	1304	1524

* Some missing data.

** Excessive missing data.

Table 1. Comparison of precipitation as obtained from hourly data through the Basin Authority's modelling procedures and as recorded from daily totals (actual precipitation). Means exclude years with one column missing.

There are several possible remedies for removal of the bias in precipitation data. Statistical methods could be used, for example, to provide estimates for dates and times when precipitation is below the hourly observation threshold or when no records were available. In fact, for some of the gages (Castle Rock, Cherry Creek Dam, Parker up to1998) the hourly values could be reconciled on a daily basis with daily records of precipitation, which are taken separately from the hourly data.

OK

Resolution of precipitation on an hourly basis would be essential if the model carried through with the use of information on individual storm intensities at specific locations in estimating total annual phosphorus load. Such methods require knowledge of the amount of precipitation during a given event, area covered by the event, and a coefficient that discounts precipitation based on characteristic percent of total precipitation that becomes runoff for a given set of site conditions (land use). This practice, which is most common for estimation of peak runoff rather than total runoff, appeared to be the initial intent of the hydrologic component of the watershed modelling. The use of individual storm-based temporal resolution was not carried over, however, into the estimation of water yield of the model, and thus is irrelevant to the estimation of water yield and to the phosphorus-loading component since the phosphorus-loading component appears to be based on total annual runoff, and not on the sum of phosphorus contributions from individual storms. For this reason, the modelling could be greatly simplified by development of an empirical relationship between total annual precipitation and total annual runoff (e.g., Hornberger et al. 1998). The underlying assumption of such an approach is that the distribution of storm types in a given year with a given amount of precipitation is very similar to the distribution of storm types in another year with the

not model basis

incorrect

Time issue

Doesn't change
months - Also
regional extra-step

same precipitation. This assumption already is inherent in the modelling because the model operates on the sum of hourly precipitation from an entire year rather than on data for individual storms. Thus, there is nothing to be lost by passing directly to simplified techniques that are based on annual runoff. In any event, continued use of hourly data will be handicapped by cessation of hourly data collection at Parker as of 1998.

Estimation of Runoff from Precipitation

The model computes annual runoff as the sum of hourly runoff over the year. Each hour in the data set is treated independently of all others. This approach potentially leads to error resulting from the effect of antecedent conditions on the amount of runoff that is derived from the rainfall occurring during a particular hour. During a storm, for example, precipitation falling initially may not generate runoff, whereas the same amount of hourly precipitation falling subsequently may generate runoff. Although the model seems to be designed for a storm-based approach, no such approach is actually implemented in the model. The degree of error caused by the discrete treatment of all hourly data observations is unknown. Antecedent conditions are mentioned, but only in connection with the correction of precipitation during a given year with information on total precipitation during the preceding year. Documentation for the model indicates that years showing above average precipitation will be treated as providing antecedent moisture for the following year, to whatever extent the observed annual precipitation exceeds the mean annual precipitation. The use of antecedent precipitation in this

incorrect

manner is not carried forward into the software, however, and thus does not influence the calculation of runoff.[1]

incorrect see Fig 4 Appen. I

The concept of effective precipitation (P_{eff}) is used in the model. For any given hour, effective precipitation is equal to total precipitation (P_{tot}) minus incipient precipitation (P_I): $P_{eff} = P_{tot} - P_I$. Effective precipitation, for modelling purposes, is defined as that which results in runoff either at the surface or under the surface.

Effective precipitation is dependent on land use.[2] Effective precipitation for undeveloped lands was assumed to be all precipitation > 0.4 inches per hour (i.e., incipient precipitation was set to 0.4 inches/hour). Because each hour is treated separately, an hour showing 0.3 inches of precipitation immediately following an hour showing 0.4 inches of precipitation would have an effective precipitation of zero. The value of 0.4 inches is taken from the Denver Urban Drainage and Flood Control Manual of 1969 (incipient precipitation is designated "depression retention" in the manual). The estimates in the manual are derived from field data that were taken from the Denver urban area, but is based on complete storm events (e.g., 0.4 inches per storm) and not on a specific time interval (e.g., inches per hour). Thus the use of the threshold procedures described in the Urban Drainage Manual is inconsistent with use of the thresholds in support of modelling.

simplifying assumpt

incorrect order of mag. - supp by UDFCD

Disagree

A different value is used for incipient precipitation in developed areas, which constitute 15% of the total drainage area for Cherry Creek. This value is set at 0.1 inches, and the value is applied separately to all hours in the annual data set. The detection limit

---

[1] Sheet: HOUR8996NEW, Page: Control and Results, Row 71 (with antecedent conditions, used only for graphs) and Row 69 (without antecedent conditions, used for all further calculations).

[2] Sheet: HOUR8996NEW, Page: User Interface, cells E5, E6.

value could be 0.15 - model refinem

for precipitation in the hourly data set is 0.1 inches. Thus, in effect, the model treats all recorded hourly precipitation as effective precipitation where developed areas are concerned. The equation that the model uses in estimating runoff is as follows: Runoff = $C * P_{eff} * A/12$. The value 12 in the formula converts inches to feet for calculation of volume. In the formula, C is a runoff coefficient, P_{eff} is as explained above, and A is area. The inclusion of C in the formula is an error insofar as it is applied to P_{eff}. The coefficient C is associated with a concept given by Chow (1964), which is frequently referenced in the model documentation. The concept (the "Rational Formula") is that maximum precipitation intensity can be discounted by an empirically determined coefficient (C) that will provide an estimate of peak runoff (not total runoff). In other words, C is a discount factor that produces an estimate of runoff from precipitation data. Possibly the same concept could be applied to total runoff for specific storm events, but the use of C cannot be combined with the use of P_{eff} because both involve a discounting concept for converting precipitation to runoff. P_{eff} is total precipitation discounted by incipient precipitation, and must be used directly for estimating total runoff from area. Alternatively, but not simultaneously, precipitation intensity could be used in estimating a value of C that could be used to estimate total runoff. Joint use of the two discounting factors leads to gross underestimation of runoff. The gross underestimation affects only runoff from undeveloped lands because runoff from developed lands in the model is based on an incipient precipitation of zero (because the detection limit for precipitation is 0.1 inch per hour, which is the value assigned to incipient precipitation).

urbanis over flow designation

incorrect

already has

not valid

A value for C was developed empirically by the modelling for undeveloped lands on the basis of recorded streamflow and recorded precipitation for two-day intervals in in your understanding

the data record. There are a number of flaws in the development of C. These should be explained, even though the use of C is actually inappropriate unless the concept of effective precipitation is abandoned for modelling purposes. A regression equation was obtained for change in streamflow at Franktown as a function of total daily precipitation (as determined by use of data for three gages) above Franktown. The slope of the line from the regression indicated that C would be 0.01, but the regression shows that precipitation accounts for only 1% of the variance in runoff for this analysis, i.e., it is not possible to predict runoff from precipitation according to this equation. Therefore, there is no justification for using the slope derived from the regression in predicting runoff.

not used to predict runoff

The empirical study of runoff is conceptually flawed in that runoff, according to the common definition and the one that is used by the modelers in their documentation, includes subsurface as well as surface flow. Subsurface flow is delayed substantially and makes up a large component of total flow. Thus, short-term relationships between total precipitation and total runoff will be erroneous to the extent that a substantial portion of the runoff occurs slowly, underground.

The degree to which the estimation procedures for runoff are valid can be judged empirically by reference to the long-term record for the Franktown gage. Figure 1 shows on an annual basis the runoff as estimated by the equations in the model as opposed to actual measurements at the Franktown gage. The Franktown gage provides a good empirical measure of total runoff because it is associated with a rock sill that forces all of the runoff to the surface where it can be measured accurately. As shown by the figure, the predicted and observed runoff differ drastically from this one-to-one relationship that is expected for a valid prediction. The equations used in the model predict annual runoff

not correct

equal to 0.2% of total precipitation, whereas the long-term record for the Franktown gage shows that long-term runoff is more than 10 times larger (4.4% of total precipitation, 1940-1960). The 4.4% number is well aligned with estimates derived by Denver Urban Drainage as reported in its analysis of data for the Denver region (DRCOG 1969). The model can be expected to underpredict runoff from undeveloped lands by about 90%. Undeveloped lands comprise 85% of the total drainage area for Cherry Creek. Thus, the error inherent in excessive discounting of runoff from undeveloped lands is quite significant and could be expected to lead to errors in all other types of predictions that require estimation of total runoff or relative importance of various sources of runoff.

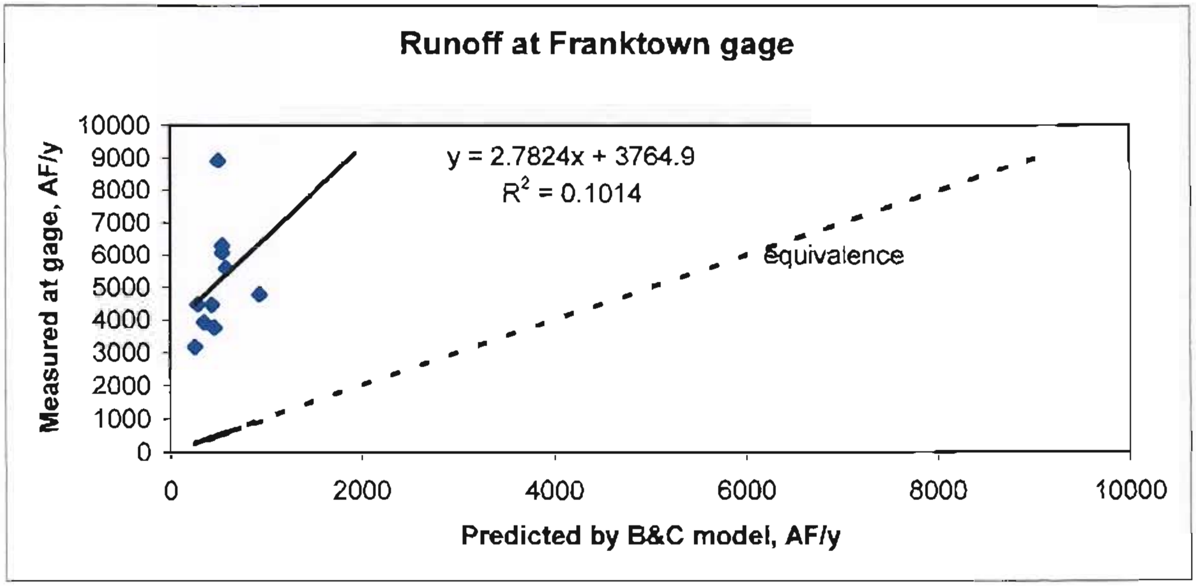

Figure 1. Relationship of measured runoff to runoff provided by the watershed model at Franktown, years 1989-1998.

Use of Corps of Engineers Data to Normalize Runoff Estimates

As mentioned in the introduction, the computed inflows to Cherry Creek Reservoir, as made annually by the Corps of Engineers, were used in normalizing the runoff estimates obtained empirically by Chadwick; the normalized data then were checked against model predictions. The comparison shows at least moderately good agreement.

The Army Corps of Engineers uses change in reservoir storage, evaporation and precipitation as estimated from empirical data, and gaged outflow from Cherry Creek Reservoir at the dam in estimating total annual inflow to Cherry Creek Reservoir. The Army Corps of Engineers is aware that substantial flow occurs through the alluvium and underneath the dam, but disregards this flow; they have chose to treat it as not being a net contributor to lake inflow. On the other hand, the Cherry Creek Reservoir modelling must include the alluvial flow, which is part of total runoff. Thus, the normalizing procedure incorrectly disregards an annual flow of approximately 4400 acre feet (about 40% of total runoff: Lewis and Saunders, 21 March 2001) as part of its normalization process. The runoff from the watershed is considerably larger than it would appear to be from the normalization process, as would be expected in view of the excessive discounting of total precipitation in the estimation of runoff.

Conclusions

A review of the hydrologic component of the watershed model for the Cherry Creek Watershed Authority shows that the software and its underlying logic contains several significant flaws. as follows.

1. Treatment of the raw data. The method that was used to obtain annual data for precipitation leads to a mean underestimate of total precipitation equaling approximately 10-24% per year, depending on gage, and larger errors for some specific years.

2. Estimation of runoff from precipitation. Two discounting concepts that can be used in converting precipitation data to estimates of runoff were inappropriately combined in the modelling. As a result, the modelling underestimates runoff from undeveloped lands by over 90%. Because phosphorus loading is estimated from runoff, this large error will carry over into loading estimates, particularly as related to the relative importance of undeveloped lands in contributing to the total P yield.

3. Use of hourly data. Use of discrete hourly data for determining effective precipitation is inconsistent with the Colorado Urban Hydrology Procedures (CUHP), which are based on storm events rather than discrete hours of precipitation.

4. Normalization of runoff data. Procedures for normalizing runoff estimates to inflow as calculated by the Army Corps of Engineers are seriously flawed in that the calculated inflow from the Army Corps of Engineers does not take into account water flowing under the dam, which amounts to approximately 40% of total runoff. Thus, model output cannot be validated against calculated inflow.

References

Chow, V. T., Editor. 1964. Handbook of Applied Hydrology. McGraw-Hill, New York.

Denver Regional Council of Governments. 1969. Urban Storm Drainage Criteria Manual. Volume 1.

Hornberger, G. M. et al. 1998. Elements of Physical Hydrology. Johns Hopkins University Press, Baltimore.

Lewis, W. M. Jr. and J. F. Saunders, III. Review and Analysis of Hydrologic Information on Cherry Creek Watershed and Cherry Creek Reservoir. March 21, 2001.