

RESEARCH ARTICLE

Use of double mass curves in hydrologic benefit evaluations

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Abstract

Environmental change resulting from intensified human interventions and climate change has impacted the hydrological function of many large river systems, largely altering the production and transport of run-off and sediment. It is thus vital to quantitatively evaluate the influence of climate change and human activities on streamflow and sediment discharge. Water balance equations, hydrological models, and comparative analyses are commonly used to fulfil this need. Double mass curves (DMCs), being one useful method for comparative analyses, are characterized by low data requirements and high transferability, and thus more practical than water balance equations and hydrological models for hydrologic benefit evaluations. However, the detailed derivation procedure of the DMC has, to date, yet been described in literature. Moreover, in previous studies, changing points of the DMC were determined either rather empirically or as the changing point of streamflow or sediment discharge (i.e., precipitation was not considered). Hence, the changing point detected may be subject to inaccuracies. This paper, for the first time, comprehensively detailed the derivation procedure of the DMC; a new way was proposed to quantitatively examine the changing point of the DMC; an example was also given to demonstrate the use of the DMC in the hydrologic benefit evaluation. It is hopeful that the method given in our paper will be widely adopted by future studies as a standard procedure to derive and use the DMC.

KEYWORDS

application example, changing points, derivation procedure, double mass curves (DMC), hydrologic benefit evaluations

1 | INTRODUCTION

Rivers play a significant role in transporting materials from land to oceans (Meybeck & Vörösmarty, 2005; Walling & Fang, 2003). Streamflow and sediment discharge from rivers are important proxies for hydrological and geomorphological processes within catchments (Siakeu, Oguchi, Aoki, Esaki, & Jarvie, 2004). Since the 1950s, environmental change driven by intensified human activities and climate change has dramatically disturbed many of the large river systems over the world (Steffen et al., 2004), changing the production and transport of run-off and sediment. It has become a hot topic to assess the climatic and anthropogenic impacts on run-off and sediment discharge.

Water balance equations, hydrological models, and comparative analyses have been employed to assess the contribution of climatic shifts and anthropogenic interventions to changes in river discharge (Gu & Tan, 1989). Water balance equations and hydrological models

assess the impact of environmental change through quantifying key components of the hydrological cycle; however, their implementation requires extensive field data collection and processing, given the intensive data requirements. Water balance equations and hydrological models are of low transferability and difficult to apply over large areas, particularly those subject to data deficiency. Comparative analyses are usually conducted through comparing field measured records from different sites with comparable environmental conditions or different periods of measurements for the same catchment. The former, as water balance equations and hydrological models, is usually labour intensive and costly given that it requires a large quantity of detailed information on the studied catchments. In contrast, the latter can easily be undertaken via a trend analysis of the studied variable. The double mass curve (DMC) is often adopted for the trend analysis for its low data requirement and high transferability. It has become a prevalent technique in the assessment of the response of river

discharges to climatic change and human disturbances (Mu, Zhang, Gao, & Wang, 2010).

The DMC is composed of cumulative values of two parameters plotted against one another over a certain time span (Searcy & Hardison, 1960). It was initially developed to examine the consistency of precipitation records (Merriam, 1937). During the past 3 decades, DMC has been frequently utilized in the evaluation of the temporal trend of hydro-meteorological data through a long time because it is an effective way of exploring the evolution of precipitation, streamflow, and sediment discharge across watersheds and quantifying the changing trends (Alansi et al., 2009; Albert, 2004; Cheng, He, Cheng, & He, 2016; Huang & Zhao, 2004; Ran, Liu, Fu, & Wang, 1996; Wang et al., 2013; Wei, Liu, & Zhou, 2013; Xin, Yu, & Han, 2015; Yao, Cai, Wei, Zhang, & Ju, 2012; Zhang, Wei, Sun, & Liu, 2012). For example, significant changes in slopes of the DMC indicate increases or decreases of the tested variable. The effect of land management and climate can be quantitatively determined via a combined analysis of shifts in the DMC slopes and local environmental conditions (Mu, Zhang, Gao et al., 2010).

Although the DMC has been widely applied in the hydrologic benefit evaluation, the detailed derivation procedure of the DMC has, to date, not been comprehensively reported in literature. A lack of a clear derivation method may lead to misuses of the DMC or in wrong conclusions about the reaction of river discharges to environmental shifts; therefore, a standard method was needed. Changing points of the DMC were traditionally determined in a rather empirical way (e.g., via eye detect or experience). In recent studies (e.g. Cheng et al., 2016; Gao, Mu, Wang, & Li, 2011; Zhang et al., 2012), changing points in the DMC were deemed to be the same as those of run-off or sediment flow and determined in terms of various methods such as those introduced in Page (1955), Hinkley (1970), Sen and Srivastava (1975), Smith (1975) and Pettitt (1979). Lacking a robust theoretical basis, traditional empirical methods are not repeatable and often obtain different changing points for the same study site when implemented by different persons. Changing points of streamflow or sediment discharge, and the DMC may not occur simultaneously because the DMC involves precipitation but the trend analysis of streamflow or sediment discharge does not; as a result, the changing points of the DMC detected by the previous methods may be subject to inaccuracies. A new repeatable method, which involves both streamflow or sediment discharge and precipitation, was thus desirable for the identification of the changing point in the DMC.

This paper aimed to detail the principle and derivation procedure of the DMC; a new approach to determining the changing point in the DMC was proposed; an example was also given to demonstrate the use of the DMC in the hydrologic benefit evaluation.

2 | THEORETICAL BASIS OF THE DMC

The DMC is a widely used approach to investigate the consistency and long-term trend of hydro-meteorological time series (Mu, Zhang, Gao et al., 2010). The method was first employed to analyse the consistency of precipitation records in order to correct the measurements,

which were sometimes subject to considerable inconsistencies driven by nonrepresentative forces (e.g., relocation of rain gauges or changes in exposure of them; Chow, 1964; Merriam, 1937). Searcy and Hardison (1960) systematically described the principle of the DMC and its applications to the long-term trend test of precipitation, streamflow, sediment flow, and facilitating and extending the use of the DMC in hydrological studies (Mu, Zhang, Gao et al., 2010). It is now also used to study sediment transport (Hindall, 1991), reservoir sedimentation (Yang, Zhao, & Belkin, 2002), and aquifer drawdown (Rutledge, 1985).

The principle of the DMC, as stated in Searcy and Hardison (1960), is that the cumulative values of one variable increase linearly with those of another if the ratio of the studied variables is a constant. In the DMC, the cumulative values of relevant variables are plotted with the x- and y- coordinates. If values of x and y axes are equally affected by external disturbances, then a DMC is a straight line; however, slope breaks are common in the DMC and present additional information on the relationship between the studied variables (Kalra & Kumar, 1989; Searcy & Hardison, 1960; Wigbout, 1973). The breaks can be driven by various factors, which impact the collection of sediment or run-off discharge such as changes in sediment or run-off flow, urbanization, revegetation or deforestation, and soil and water conservation measures and climate change. Most importantly, slope breaks are able to help determine the time for the occurrence of a change in the DMC (i.e., change-point year) (Searcy & Hardison, 1960). Generally, a slope break can be ignored if it lasts no more than 5 years, otherwise, it should be treated as a trend and further studied (Searcy & Hardison, 1960). Once the change-point year has been determined, records for the relevant variables would be checked to determine whether there were any anthropogenic disturbances before the change-point year. It can be concluded that slope changes are driven by natural causes if there were no anthropogenic disturbances; otherwise, the changes may result from human activities, and a further study can be undertaken to quantitatively assess the impact of natural causes and human activities for the period after the change-point year. In hydrological studies, the DMC is often used to quantify the relative impact of climate (i.e., precipitation) and human activities (i.e., land use) on the change of total streamflow and sediment discharge for the period after the transition years (Gao, Geissen, Ritsema, Mu, & Wang, 2013). Such work is useful for policy makers to optimize land use patterns and improve the sustainability of eco-environment.

3 | DERIVATION OF THE DMC

The derivation of the DMC for hydrological benefit evaluations includes four steps, which are the establishment of a plot between cumulative annual precipitation and streamflow or sediment discharge, detection of changing points in the DMC, estimation of the total variation of run-off (ΔR_c) and sediment flow (ΔS_c) over the time after the change-point year, and determination of the relative effect of precipitation and anthropogenic disturbances. They are detailed in the following paragraphs, in which T_i represents a time series whereas P_i , R_i , and S_i stand for precipitation, run-off, and sediment discharge at

i year, respectively. It should be noted that in the DMC, other precipitation-related factors (e.g., rainfall intensity of flood seasons) can also be used to develop relationships with streamflow or sediment discharge. Here, we used annual precipitation as an example.

Step 1. Establishing the DMC.

This step includes the calculation of cumulative precipitation (ΣP), run-off (ΣR) and sediment discharge (ΣS), and plotting of ΣP versus ΣR (or ΣP versus ΣS). In general, vertical axis is the tested variable (i.e., ΣR or ΣS) whereas horizontal axis is the reference variable (i.e. ΣP ; Figure 1).

$$\Sigma P = \sum_{i=1}^n P_i \quad (1)$$

$$\Sigma R = \sum_{i=1}^n R_i \quad (2)$$

$$\Sigma S = \sum_{i=1}^n S_i \quad (3)$$

Step 2. Detecting changing points of the DMC

Actually identification of changing points is to find the turning points of the DMC slope (k) (i.e., slope breaks). For the DMC shown in Figure 1, the slope (k) can be expressed as

$$k_{i+1} = \tan\theta = \frac{\Delta R}{\Delta P} = \frac{\Sigma R_{i+1} - \Sigma R_i}{\Sigma P_{i+1} - \Sigma P_i} \quad (4)$$

In order to avoid the shortfalls of previous methods (i.e., empirical methods and the direct use of changing points in streamflow or sediment discharge), a nonparametric method proposed by Pettitt (1979) was employed to identify changing points of the DMC slope (k). This method determines a significant change in the mean of a time series when the occurrence of them is unassured. The test utilizes the

Mann-Whitney statistic $U_{t,N}$ that examines if two sample sets (x_1, \dots, x_t and x_{t+1}, \dots, x_N) come out of the same population. The test statistic $U_{t,N}$ is defined as

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^N \text{sgn}(X_t - X_j) \quad \text{for } t = 2, \dots, N \quad (5)$$

and

$$\begin{aligned} \text{if } (X_t - X_j) > 0, & \quad \text{sgn}(X_t - X_j) = 1 \\ \text{if } (X_t - X_j) = 0, & \quad \text{sgn}(X_t - X_j) = 0 \\ \text{if } (X_t - X_j) < 0, & \quad \text{sgn}(X_t - X_j) = -1. \end{aligned} \quad (6)$$

$U_{t,N}$ counts the times for which members of the first sample are over those of the second. In the Pettitt's test, the null hypothesis has no changing point. The test statistic K_N and the associated probability (P) are derived as below:

$$K_N = \max_{1 \leq t \leq N} |U_{t,N}| \quad (7)$$

$$P \approx 2 \exp\left\{-6(K_N)^2 / (N^3 + N^2)\right\}. \quad (8)$$

Step 3. Estimating the total variation in run-off (ΔR_c) and sediment discharge (ΔS_c) over the period following the change-point years.

Once the change-point year (T_b) has been determined in Step 2, regression equations can be developed based on the data points for the period before T_b :

$$\Sigma R = a_1 \Sigma P + b_1 \quad (9)$$

$$\Sigma S = a_2 \Sigma P + b_2. \quad (10)$$

The cumulative run-off (ΣR_c) and sediment discharge (ΣS_c) at T_n year are derived through taking the cumulative precipitation over the

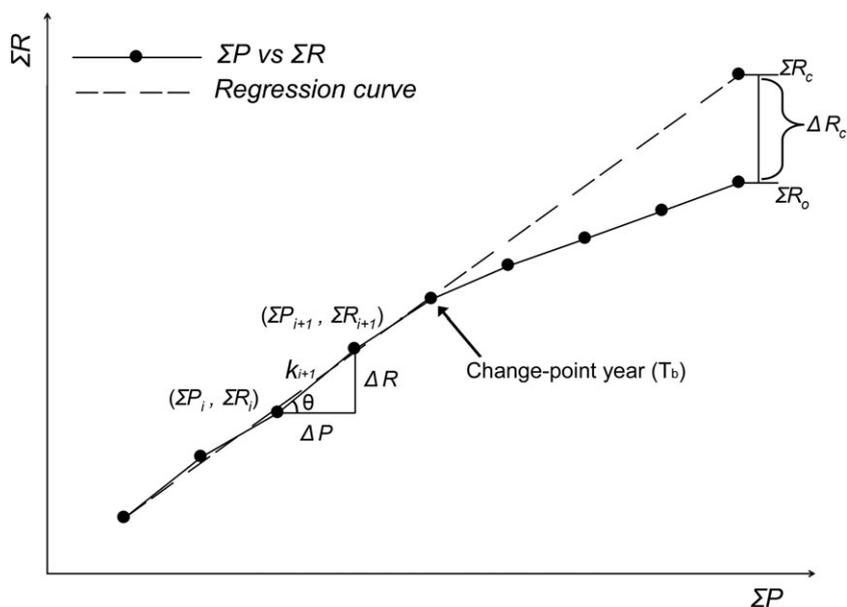


FIGURE 1 Sketch of the double mass curve of precipitation versus run-off

whole study period (ΣP) as the input of the regression Equations 9 and 10. The total variation of run-off (ΔR_c) and sediment (ΔS_c) over the time following the change-point year can then be expressed as (Figure 1)

$$\Delta R_c = \Sigma R_c - \Sigma R \quad (11)$$

$$\Delta S_c = \Sigma S_c - \Sigma S. \quad (12)$$

Then, the run-off or sediment reduction rate (η_R or η_S) can be expressed as

$$\eta_R = \frac{\Delta R_c}{\Sigma R_c} \times 100\% \quad (13)$$

$$\eta_S = \frac{\Delta S_c}{\Sigma S_c} \times 100\%. \quad (14)$$

Step 4. Identifying the relative effect of precipitation and anthropogenic disturbances on changes in streamflow or sediment discharge.

The relative influence of precipitation and anthropogenic disturbances on streamflow and sediment shifts can be determined according to the procedure presented in Table 1. In the table, \bar{R}_b and \bar{R}_a represent observed mean annual run-off or sediment for a certain period before and after the transition year. Total change in run-off or sediment (ΔR) equals the discrepancy between \bar{R}_b and \bar{R}_a . Predicted mean annual run-off and sediment for a certain period (e.g., say 10 years) after the change-point year, \bar{R}_{ca} can then be derived on the basis of the run-off and sediment predicted by Equations 9 and 10 for individual years. The discrepancy between \bar{R}_b and \bar{R}_{ca} indicates the effect of precipitation change (ΔP), whereas the difference of \bar{R}_a and \bar{R}_{ca} or between ΔR and ΔP is attributed to human interventions.

4 | AN APPLICATION EXAMPLE FOR THE DMC

4.1 | Study area and datasets

In order to further clarify the derivation and use of the DMC, the above four steps were applied to assess the hydrologic benefit in the middle reaches of the Yellow River (MRYR) during 1957–2008 (Table 2). The region is located within 104°E–113°E and 32°N–42°N,

with an area of 344,000 km². In this study, annual precipitation was collected at 33 meteorological stations across the region. They were provided by the National Meteorological Information Centre and China Meteorological Administration. Annual streamflow and sediment discharge for the study region were derived on the basis of measurements of two key hydrological stations (i.e., Toudaoguai and Huayuankou) provided by the Chinese River Streamflow and Sediment Communiques, the Ministry of Water Resources of PRC. All the measured data underwent a strict quality control process conducted by corresponding agencies.

4.2 | Application of the DMC

Following Step 1, we established the DMC of ΣP versus ΣR and ΣP versus ΣS (Figure 2).

Proceeding to Step 2, we detected the change-point year in the DMC of ΣP versus ΣR and ΣP versus ΣS (Figure 3). The change-point year is 1990 for the ΣP versus ΣR and 1981 for the ΣP versus ΣS .

For Step 3, the total variation of run-off (ΔR_c) and sediment discharge (ΔS_c) through the time following the change-point years was estimated.

Given that the change-point years of 1990 and 1981 were found for streamflow and sediment discharge, respectively; the regression equations were established for the period before 1990 and 1981 and then employed to estimate the run-off and sediment until 2008. The estimated ΣR_c and ΣS_c were presented in Tables 3 and 4. The total variation of run-off (ΔR_c) and sediment (ΔS_c) after the change-point year were $1,559.22 \times 10^8 \text{ m}^3$ and $154.45 \times 10^8 \text{ t}$, respectively. The reduction rate of run-off (η_R) and sediment discharge (η_S) were 16.2% and 28.0%, respectively (Tables 3 and 4).

Lastly, Step 4 estimated the relative effect of precipitation and anthropogenic disturbances on run-off and sediment changes. The average contribution of human interventions to run-off reduction was 78.5% between 1991 and 2008, which was much higher than that of precipitation (21.5%; Table 5). Similarly, human interventions (90.4%) also contributed more than precipitation (9.6%) to sediment reductions between 1982 and 2008 (Table 6). These results suggested that anthropogenic interventions dominated the decline of run-off and sediment discharge over the MRYR basin throughout last 3 decades.

5 | DISCUSSION

In the paper, we detailed the derivation of the DMC and gave an example demonstrating the use of DMC in hydrological benefit

TABLE 1 The procedure for the determination of the impacts of climate change and human interventions on run-off or sediment flux

Period	Observed mean	Modelled mean	Total change		Impact of precipitation		Impact of human intervention	
			Amount (ΔR)	Percentage ($\Delta R\%$)	Amount (ΔP)	Percentage ($\Delta P\%$)	Amount (ΔH)	Percentage ($\Delta H\%$)
Reference	\bar{R}_b	—	—	—	—	—	—	—
Disturbed	\bar{R}_a	\bar{R}_{ca}	$\bar{R}_b - \bar{R}_a$	$\frac{\Delta R}{\bar{R}_b} \times 100\%$	$\bar{R}_{ca} - \bar{R}_b$	$\frac{\Delta P}{\Delta R} \times 100\%$	$\bar{R}_{ca} - \bar{R}_a$ or $\Delta R - \Delta P$	$\frac{\Delta H}{\Delta R} \times 100\%$

TABLE 2 The datasets used in the application of the double mass curves over the middle reaches of the Yellow River basin between 1957 and 2008

Year	Annual precipitation P_i (mm)	Annual run-off R_i (10^9m^3)	Annual sediment S_i (10^8t)	Cumulative precipitation ΣP (mm)	Cumulative run-off ΣR (10^8m^3)	Cumulative sediment ΣS (10^8t)	Extrapolate cumulative run-off ΣR_c (mm)	Extrapolate cumulative sediment ΣR_c (10^8t)	Calculated annual run-off R_{ci} (10^9m^3)	Calculated annual sediment S_{ci} (10^8t)
1957	464.70	188.70	8.42	464.70	188.70	8.42	418.00	10.82	418.00	10.80
1958	689.50	356.40	26.37	1,154.20	545.10	34.79	660.29	25.10	242.29	14.27
1959	538.50	148.60	18.85	1,692.70	693.70	53.64	849.51	36.24	189.23	11.15
1960	447.20	13.20	4.68	2,139.90	706.90	58.32	1,006.66	45.50	157.15	9.26
1961	658.10	242.50	1.65	2,798.00	949.40	59.97	1,237.92	59.12	231.26	13.62
1962	475.00	237.40	3.74	3,273.00	1,186.80	63.71	1,404.83	68.96	166.92	9.83
1963	542.40	286.90	6.32	3,815.40	1,473.70	70.03	1,595.43	80.18	190.60	11.23
1964	787.90	488.20	13.35	4,603.30	1,961.90	83.38	1,872.30	96.49	276.87	16.31
1965	383.90	192.30	5.99	4,987.20	2,154.20	89.37	2,007.20	104.44	134.90	7.95
1966	549.30	198.60	17.22	5,536.50	2,352.80	106.59	2,200.23	115.81	193.02	11.37
:	:	:	:	:	:	:	:	:	:	:
2000	450.80	25.10	0.55	22,643.90	7,279.90	391.28	8,211.77	469.93	158.41	9.33
2001	438.20	52.20	0.46	23,082.10	7,332.10	391.74	8,365.75	479.00	153.98	9.07
2002	465.00	72.80	0.89	23,547.10	7,404.90	392.63	8,529.15	488.63	163.40	9.63
2003	700.00	157.10	1.69	24,247.10	7,562.00	394.32	8,775.13	503.12	245.98	14.49
2004	461.30	112.90	1.80	24,708.40	7,674.90	396.12	8,937.23	512.67	162.10	9.55
2005	448.50	106.80	0.65	25,156.90	7,781.70	396.77	9,094.83	521.95	157.60	9.28
2006	457.80	106.20	0.20	25,614.70	7,887.90	396.97	9,255.71	531.43	160.87	9.48
2007	529.10	80.40	0.12	26,143.80	7,968.30	397.09	9,441.63	542.38	185.93	10.95
2008	449.30	72.00	0.14	26,593.10	8,040.30	397.23	9,599.52	551.68	157.88	9.30

evaluations. The key message that our paper delivered was to provide a clear and repeatable method for the derivation and use of DMC, facilitating future applications of the DMC in hydrological benefit evaluations. We proposed a new way of determining the slope breaks of the DMC. The method quantitatively examines the slope of the DMC itself and the break in the slope, taking account of the impact of precipitation on the occurrence of the slope break (i.e., changing point). This strategy is different from traditional methods, in which the slope break was determined either in an empirical (or qualitative) and unrepeatably way (e.g., by eye detect) or as the change point of streamflow or sediment discharge (Gao, Mu et al., 2011; Gao, Geissen et al., 2013). Gao, Mu et al. (2011) examined changing points of streamflow discharge from the MRYS between 1957 and 2008 using the Pettitt's test based on the dataset used in our study. They found that the change-point year for the streamflow discharge was 1985, which is different from the change-point year for the DMC between precipitation and streamflow discharge detected in our study (1989). The difference demonstrates that it is necessary to take into account the impact of precipitation during the detection of the DMC changing point. Overall, our method for the changing point detection makes more sense in terms of the principles of the DMC, and it should be able to yield more reasonable results.

We employed the Pettitt's test to identify the changing point in the DMC slope. The Pettitt's test is a widely applied statistical analysis in hydrological studies partly because it is able to effectively identify a statistically significant changing point for a given variable (Gao, Mu

et al., 2011; Gao, Geissen et al., 2013; Mu, Zhang, McVicar, Chille, & Gau, 2007). Mann-Kendall test is also a popular method used for trend analyses and change-point detections. Unlike the Pettitt's test, the Mann-Kendall test usually produces several possible results when used to detect changing points of a given variable (Mu, Zhang, McVicar et al., 2007). However, during the application of the DMC in hydrological benefit evaluations, only one changing point is needed to determine periods with or without human activities (Mu, Zhang, Gao et al., 2010). The Pettitt's test was thought to be more suitable for the DMC than the Mann-Kendall test.

The application example showed that for the MRYS, human activities were the dominant factor for the changes in streamflow and sediment discharge since the 1980s, and the changing point for streamflow (1990) occurred earlier than that for sediment discharge. The results are consistent with previous studies in the region (e.g., Gao, Mu et al., 2011, Zhu et al., 2015, Mu et al., 2012), indirectly confirming that the DMC produced reasonable results and the new method we proposed for the change-point detection worked well. The dominance of anthropogenic activities may be a result of (a) increased demand for water resources in the Yellow River due to national economic development (Liu & Zhang, 2004), (b) soil and water conservation programs and eco-environment rehabilitation campaign on the Loess Plateau (Gao et al., 2010; Mu et al., 2007), (c) the construction of water control projects (e.g., reservoirs) (Tian, Cui, Xu, & Zhou, 2005; G. Wang, Wu, & Wang, 2005). In addition, there have been a large scale of soil and water conservation measures (e.g., check

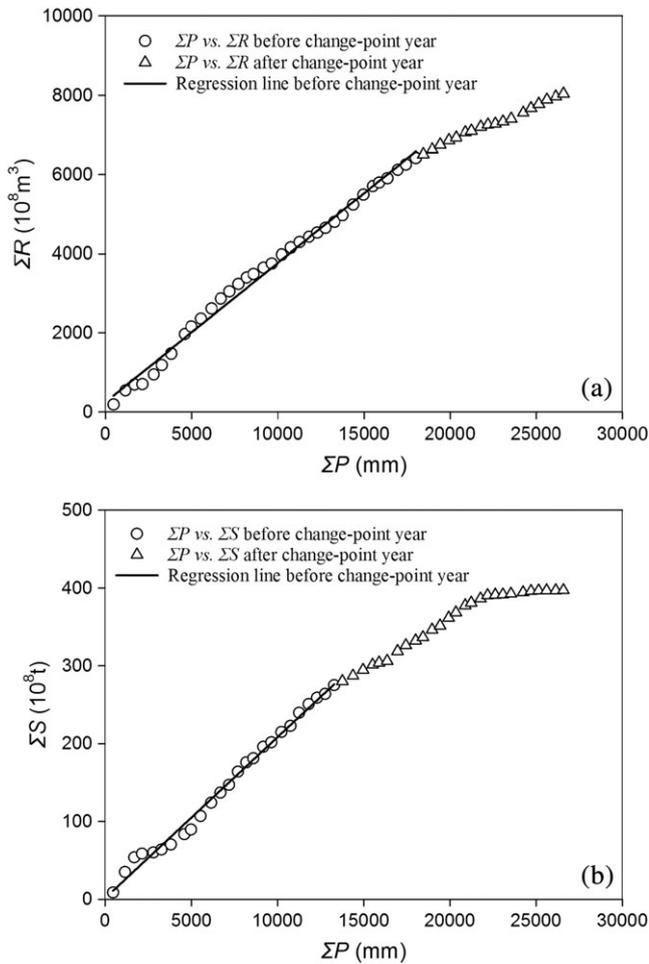


FIGURE 2 The double mass curve of (a) ΣP versus ΣR and (b) ΣP versus ΣS in middle reaches of the Yellow River

dams, terraces) on the Loess Plateau since the 1970s (P. F. Li, Mu, Holden et al., 2017; Zhao, Mu, Wen, Wang, & Gao, 2013). Such measures were more influential on soil erosion than run-off given that they were mainly designed to reduce the severe soil erosion on the plateau, leading to a more rapid reduction of sediment discharge and eventually an earlier change point in the slope of streamflow DMC.

In addition to the DMC, water balance equations and hydrological models are also useful tools for hydrological benefit evaluations. They are able to account for the contribution of climate change and different land management practices to final shifts in streamflow or sediment discharge, on the basis of a quantitative assessment of different components (e.g., soil moisture, evapotranspiration, and overland flow) of hydrological cycles. However, water balance equations and hydrological models need extensive antecedent work (e.g., field experiments) and massive data to implement, limiting their use in areas without sufficient data support. For example, soil and water assessment tool (SWAT) model has been frequently used in hydrological benefit evaluations through operating based on possible climate change and land use change scenarios (e.g., E. H. Li, Mu, Zhao, Gao, & Sun, 2016; Zuo et al., 2016). However, the implementation of SWAT model requires a large amount of data on topography, climate, soil, and land use (Neitsch, Arnold, Kiniry, Williams, & King, 2011). In many places, some of these data are not available, or the accuracy of the data is

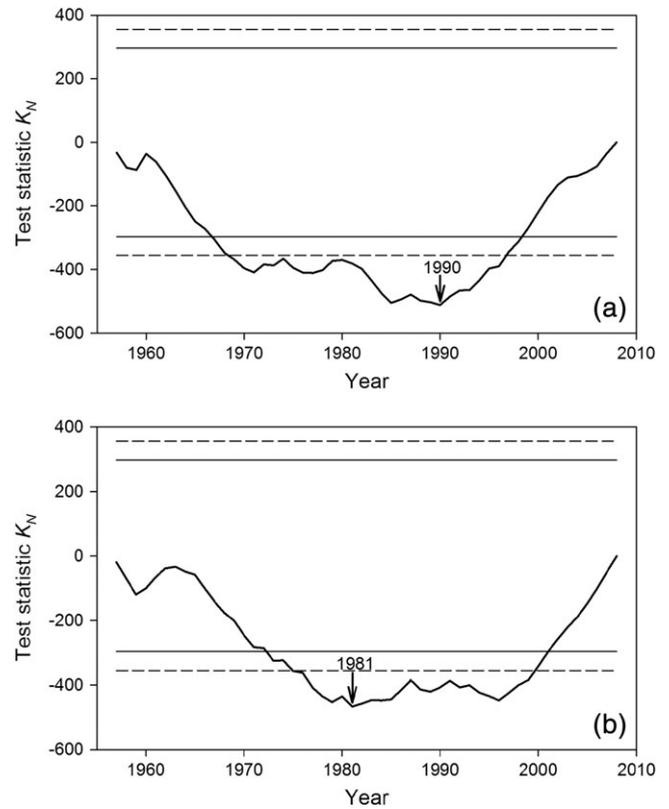


FIGURE 3 The Pettitt test for detection of slope changes (k) in the double mass curve of (a) ΣP versus ΣR and (b) ΣP versus ΣS . Horizontal lines represent the 1% (dotted) and 5% (solid) significance levels

limited (P. H. Li, Mu, Holden et al., 2017). As a result, it is difficult to apply the SWAT model to these places or modelling results may be subject to unacceptable uncertainties. Data requirement of the DMC is much less than water balance equations and hydrological models; it is able to produce reliable results on the basis of widely available precipitation data (e.g., annual precipitation or rainfall intensity for flood seasons) and streamflow or sediment discharge at catchment outlets (Mu, Zhang, Gao et al., 2010). The DMC provides an easy and effective alternative to water balance equations and hydrological models.

TABLE 3 Linear regression equations of ΣP vs. ΣR for the period before the changing-point year in the middle reaches of the Yellow River basin

Regression equation	ΣR_c ($10^8 m^3$)	ΣR_o ($10^8 m^3$)	ΔR_c ($10^8 m^3$)	η_R (%)
$\Sigma R = 0.3514 \Sigma P + 254.7$ ($R^2 = 0.9917$, $N = 34$)	9,599.52	8,040.30	1,559.22	16.2

TABLE 4 Linear regression equations of ΣP vs. ΣS for the period before the change-point year in the middle reaches of the Yellow River basin

Regression equation	ΣS_c ($10^8 t$)	ΣS_o ($10^8 t$)	ΔS_c ($10^8 t$)	η_S (%)
$\Sigma S = 0.0207 \Sigma P + 1.205$ ($R^2 = 0.9915$, $N = 25$)	551.68	397.23	154.45	28.0

TABLE 5 The impact of precipitation and human interventions on run-off decline of the middle reaches of the Yellow River basin during different decades

Period	Observed mean (10 ⁸ m ³)	Modelled mean (10 ⁸ m ³)	Total change		Impact of precipitation		Impact of human intervention	
			Amount (10 ⁸ m ³)	Percentage (%)	Amount (10 ⁸ m ³)	Percentage (%)	Amount (10 ⁸ m ³)	Percentage (%)
Before 1990	188.67							
1991–1999	93.34	163.33	95.32	50.5	25.34	26.6	69.98	73.4
2000–2008	87.28	171.80	101.39	53.7	16.87	16.6	84.52	83.4
1991–2008	90.31	167.56	98.36	52.1	21.11	21.5	77.25	78.5

TABLE 6 The impact of precipitation and human interventions on sediment discharge decline of the middle reaches of the Yellow River basin during different decades

Period	Observed mean (10 ⁸ t)	Modelled mean (10 ⁸ t)	Total change		Impact of precipitation		Impact of human intervention	
			Amount (10 ⁸ t)	Percentage (%)	Amount (10 ⁸ t)	Percentage (%)	Amount (10 ⁸ t)	Percentage (%)
Before 1981	11.00							
1982–1989	6.42	10.76	4.59	41.7	0.24	5.3	4.34	94.7
1990–1999	6.43	9.82	4.58	41.6	1.18	25.8	3.39	74.2
2000–2008	0.72	10.12	10.28	93.4	0.88	8.6	9.40	91.4
1982–2008	4.52	10.38	6.48	58.9	0.62	9.6	5.86	90.4

6 | CONCLUDING REMARKS

The derivation and use of the DMC in a hydrologic evaluation were systematically presented in the paper for the first time. A new method was proposed to determine the slope break of the DMC, given that the existing approaches were of empirical nature or did not consider the impact of precipitation. On the basis of the measurements from the middle reaches of the Yellow River, China, an example was given to demonstrate the application of the DMC. The procedure presented in this study provides a clear and repeatable method for the derivation and use of the DMC. We believe that this method will be widely used by future studies on the hydrologic benefit evaluation.

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