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南水北调中线总干渠典型渠段水体自净能力研究

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摘要:水体自净能力是影响水质指标变化的重要因素。以 BOD_5 降解系数作为自净能力表征,选取南水北调中线总干渠河南段程沟、方城、沙河南、兰河北、新峰、苏张等 6 个监测断面 2015 年 1 月至 2015 年 7 月逐月 BOD_5 监测数据和研究渠段各节制闸的流量、水深等数据,采用稳态一维 BOD_5 降解模型对总干渠 BOD_5 降解系数进行拟合。结果表明,研究渠段 BOD_5 降解系数数值范围为 0.024/d～0.054/d,与其他区域相比,总干渠的水体自净能力相对较小。研究渠段 BOD_5 降解系数季节变化明显,1—4 月、7 月的拟合 k 值分别为 0.028 /d($p<0.05$),0.033/d($p<0.05$),0.024 /d($p<0.05$),0.039 /d($p<0.05$),0.054 /d($p<0.05$);但 5 月、6 月的拟合 k 值均不具有统计显著性($p>0.05$),可能是由于桥面和路面降雨径流形成了外源有机物污染输入,造成渠道 BOD_5 浓度波动较大。总干渠自净能力受温度影响显著,BOD_5 降解系数基本随温度的升高而增大,温度校正系数 θ 值为 1.039。

关键词:自净能力;南水北调;中线总干渠;BOD_5;降解系数

中图分类号:TV68;X830.3　**文献标志码:**A　**开放科学(资源服务)标志码(OSID):**

南水北调中线工程是我国重要水资源战略配置工程,工程通水后给沿线地区带来了巨大的社会、经济和生态效益,保障了沿线省市社会经济的正常发展。然而,中线工程运行以来,由于总干渠结构复杂,空间跨度大,生态系统类型独特,输水水质保障工作面临巨大的挑战。南水北调中线总干渠全长 1 432 km,长距离输水使得影响水质变化的因素复杂多样,如渠道本身的水体自净因素,渠道外的大气干湿沉降、桥面和坡面雨水径流等。研究水体自净能力,对于认识总干渠水质的变化趋势,总结其变化规律都有重要意义。

有机物的降解系数是水体自净能力的重要表征指标[1],已有研究多通过有机物降解过程的测定和模拟得到降解系数的大小。如蔡建楠等[2]根据稳态一维 BOD_5(五日生化需氧量)降解模型对研究河段的 BOD_5 降解系数进行推算;慕金波等[3]利用室内实验研究,采用最小二乘法估计出了南四湖及入湖河流的 BOD_5 降解系数;李俊斌[4]根据水质监测资料统计分析计算出主要污染物包括 BOD_5 在漳泽水库的降解系数;刘鸿亮等[5]通过投放示踪剂监测得到浓度时间过程线,从而得到 BOD_5 降解系数;还有学者利用已有的研究成果,与研究河流的实际情况进行类比分析确定 BOD_5 降解系数[6]。近年来,一些影响河湖水体自净能力的关键影响因素,如气候变化引起的温度升高[7]、污废水排放[8-9]对河流自净能力的影响也逐渐受到关注。

目前对于天然河流的自净能力已经有大量的研究成果,但是对于南水北调中线总干渠这类大

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型人工输水渠道的自净能力还缺乏深入的认识。与天然河流相比,人工输水渠道通常具有生境结构单一、水体流态均匀、人工调控程度高等特征[10],其自净能力可能与天然河流存在较大的差异。因此,本文以南水北调中线总干渠 BOD_5 监测数据为基础,通过水质监测资料的统计分析,计算总干渠 BOD_5 降解系数,为认识总干渠水体自净能力提供参考。

1　数据和方法

1.1　基础数据

水体 BOD_5、水温数据选取南水北调中线总干渠河南段程沟、方城、沙河南、兰河北、新峰、苏张等 6 个监测断面 2015 年 1 月至 2015 年 7 月逐月监测数据,监测断面分布见图 1。BOD_5 测定采用《地表水环境质量标准》(GB 3838—2002)规定的国标方法(GB 7488—87)。

图 1　南水北调中线总干渠研究渠段水质监测断面分布位置示意图

研究渠段有节制闸 13 处,节制闸之间流速可能存在差异。为计算渠道流速和过流时间,收集整理研究渠段(程沟—苏张段)各节制闸的流量逐月平均值,闸前水深逐月平均值、闸后水深逐月平均值,两相邻节制闸之间的渠道边坡系数、渠底宽度等参数,具体见表 1。

表 1　研究渠段监测断面和节制闸以及对应的参数情况

监测断面	节制闸	距渠首距离/km	1 月至 7 月平均流量/($m^3 \cdot s^{-1}$)	其他参数
程沟		93		
	十二里河节制闸	97	53.507	
	白河节制闸	116	52.785	
	东赵河节制闸	137	52.095	
	黄金河节制闸	159	52.264	
	草墩河节制闸	181	53.108	包括: (1)流量逐月平均值 (2)闸前水深逐月平均值 (3)闸后水深逐月平均值 (4)两相邻节制闸之间的渠道边坡系数 (5)渠底宽度
方城		195		
	澧河节制闸	209	50.480	
	澎河节制闸	232	52.356	
沙河南		238		
	沙河节制闸	241	49.480	
	玉带河节制闸	266	50.053	
	北汝河节制闸	279	50.477	
兰河北	兰河节制闸	300	49.134	
新峰		315		
	颍河节制闸	327	52.058	
	小洪河节制闸	348	47.955	
苏张		354		

1.2　BOD_5 降解系数计算方法

1.2.1　BOD_5 降解系数拟合模型

降解系数的确定采用稳态一维 BOD_5 降解模型[11],为

$$c_t = c_0 \cdot \exp(-kt) \tag{1}$$

式中:c_t 为 t 时刻 BOD_5 浓度,mg/L;c_0 为 BOD_5 的初始浓度,mg/L;k 为 BOD_5 的降解系数,1/d;t 为过流时间,d。

由(1)式得

$$\ln\left(\frac{c_0}{c_t}\right) = kt \tag{2}$$

由式(2)可知,$\ln(c_0/c_t)$与 t 呈线性关系,通过 6 个监测断面的 BOD_5 值,计算初始断面与每一个断面之间的降解时间 t 和 $\ln(c_0/c_t)$,并绘制 $\ln(c_0/c_t)$ 与 t 散点图。对散点作线性回归,得到降解方程,其斜率即可视为总干渠 BOD_5 降解系数。散点图和线性回归分析均在 SPSS18.0 中执行。

1.2.2　过流时间计算方法

为准确计算水体在不同断面之间的过流时间,首先计算研究渠段的流速分布情况。相邻两节制闸之间流速相对均一,其平均流速计算方法为

$$\begin{cases} h=\frac{1}{2}(h_1+h_2) \\ A=(b+mh)h \\ v=q/A \end{cases} \quad (3)$$

式中:h 为两相邻节制闸之间的平均水深,m;h_1 为前一个节制闸的闸后水深,m;h_2 为后一个节制闸的闸前水深,m;A 为过水断面面积,m^2;b 为渠底宽度,m;m 为边坡系数;q 为流量,m^3/s;v 为两相邻节制闸之间的平均流速,m/s。

两相邻节制闸之间的过流时间按照式(4)计算

$$t=\frac{S}{v}\times\frac{1}{3600\times 24} \quad (4)$$

式中:t 为两相邻节制闸之间的过流时间,d;S 为两相邻节制闸之间的距离,m;v 为两相邻节制闸之间的平均流速,m/s。

1.3　温度对 BOD_5 降解系数的影响分析

温度是影响水体自净能力最为基础的因素。南水北调中线总干渠位于我国北方,不同月份之间温度差异明显,因此本研究重点关注温度对 BOD_5 降解系数的影响。一般来说,温度对降解系数的影响可以通过温度校正系数表征[6],为

$$k_T=k_{T_0}\theta^{(T-T_0)} \quad (5)$$

式中:k_T 为温度 T 对应的降解系数,1/d;k_{T_0} 为温度 T_0 对应的降解系数,1/d;T,T_0 为温度,℃;θ 为温度校正系数。

由(5)式两边取对数,整理得

$$\ln k_T-\ln k_{T_0}=(T-T_0)\ln\theta \quad (6)$$

由式(6)可知,$\ln k_T-\ln k_{T_0}$ 与 $T-T_0$ 成正比关系,比例系数为 $\ln\theta$。基于计算得到的不同月份 BOD_5 降解系数及其对应的平均水温,将不同月份进行两两组合,绘制($\ln k_T-\ln k_{T_0}$)与($T-T_0$)散点图。对散点作线性回归,通过其斜率 $\ln\theta$ 可计算得到温度校正系数 θ。散点图和线性回归分析均在 SPSS18.0 中执行。

2　结果与分析

2.1　研究渠段 BOD_5 浓度及水温变化

BOD_5 和水温的沿程变化趋势见图 2。BOD_5 总体呈现出沿程下降的趋势,但时间变化规律不明显。其中程沟断面平均为 2.1 mg/L,方城和沙河南断面平均值下降为 1.9 mg/L,兰河北断面平均值进一步下降至 1.6 mg/L,新峰断面平均值有所上升,为 1.7 mg/L,苏张断面平均值进一步下降至 1.5 mg/L。时间尺度上,程沟断面 BOD_5 在 2、7 月最高为 2.6 mg/L,5 月最低为 1.6 mg/L,2—5 月逐步下降;方城断面 2 月最高为2.4 mg/L,7 月最低为 1.5 mg/L;沙河南断面 2 月最高为 2.4 mg/L,3 月最低为1.5 mg/L;兰河北断面 5 月最高为1.9 mg/L,2 月最低为1.3 mg/L,2—5 月逐步升高;新峰断面 6 月最高为2.3 mg/L,5 月最低为 1.4 mg/L;苏张断面 5 月最高为1.8 mg/L,1 月最低为1.1 mg/L。

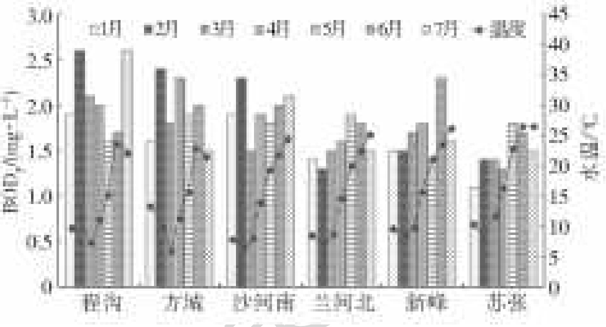


图 2　南水北调中线总干渠(程沟—苏张段)BOD_5 和水温沿程变化情况

水温则显现出明显的时间变化规律,断面之间的差异相对较小。各断面水温基本都在 8～28 ℃,其中程沟断面 3 月最低为 8.4 ℃,6 月最高为 27.1 ℃;方城断面 3 月最低为 7.9 ℃,6 月最高为 27.5 ℃;沙河南断面 2 月最低为 6.6 ℃,7 月最高为 26.8 ℃;兰河北断面 2 月最低为 6.7 ℃,7 月最高为 26.9 ℃;新峰断面 2 月最低为 7.0 ℃,7 月最高为 27.1 ℃;苏张断面 2 月最低为 7.3 ℃,7 月最高为 27.3 ℃。1—3 月水温相对较低,3—7 月水温上升趋势显著。

2.2　研究渠段 BOD_5 降解系数计算结果

2.2.1　流速和过流时间的分布情况

流速和过流时间的计算结果见图 3。1—3 月流速沿程下降趋势比较明显,其中 1 月流速最高为 0.25 m/s,最低为 0.14 m/s;2 月流速最高 0.18 m/s,最低 0.11 m/s;3 月流速最高 0.25 m/s,最低 0.18 m/s。4—7 月平均流速明显升高,但波动较大,其中 4 月最大 0.34 m/s,最低 0.23 m/s;5 月最高 0.29 m/s,最低 0.24 m/s;6 月最高 0.46 m/s,最低 0.27 m/s;7 月最高 0.39 m/s,最低 0.30 m/s。平均来看,总干渠流速总体呈沿程下降趋势,平均流速在 0.26 m/s。

以程沟断面为起始,过流时间与沿程流速呈反比关系。1 月过流时间为 16.4 d,2 月流速最慢,过流时间为 22 d,3 月过流时间为 14.1 d,4—7 月过流时间均为 9 d 左右。按平均流速计算,过流时间为 11.3 d。

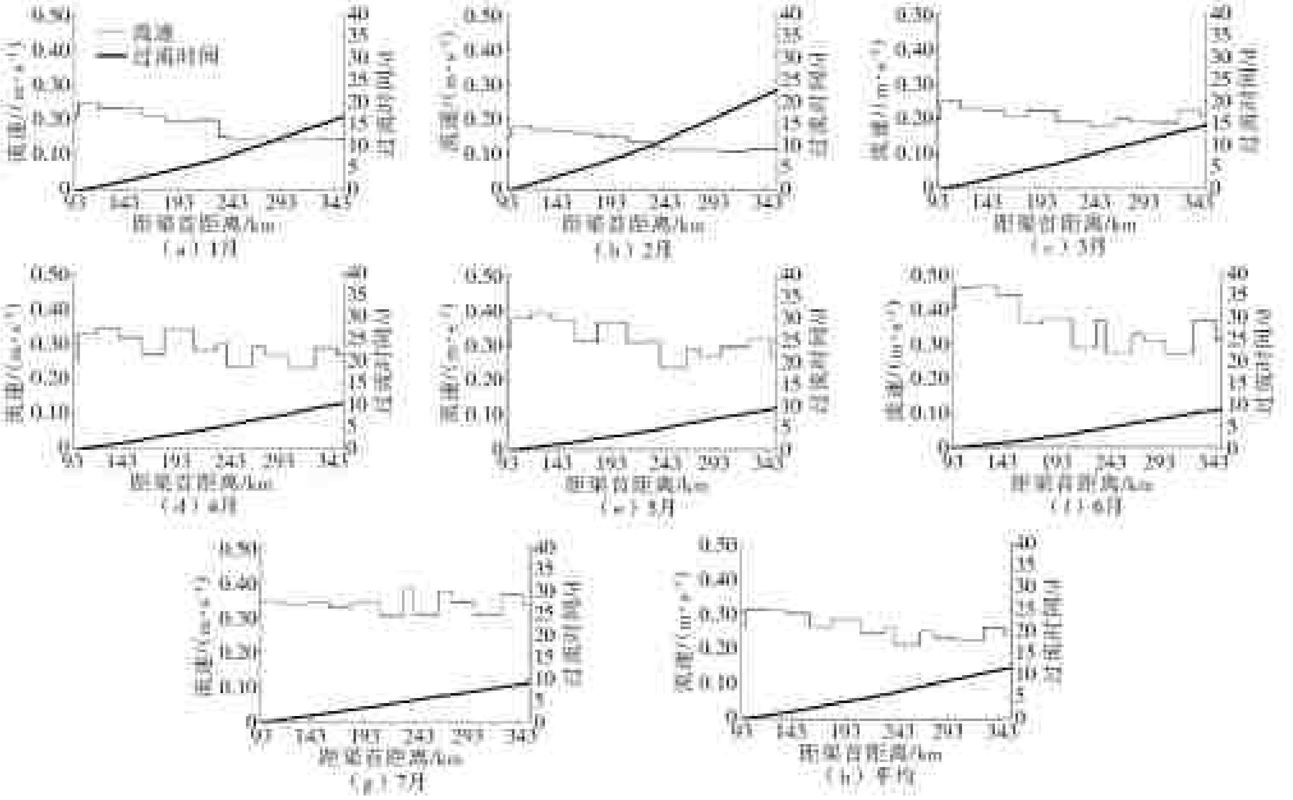


图 3　南水北调中线总干渠(程沟—苏张段)流速分布和过流时间

2.2.2　BOD$_5$ 降解系数的拟合结果

对 1—7 月以及所有月份平均降解系数进行回归拟合,散点分布和拟合结果见图 4。散点图显示,1—4 月、7 月份以及平均值 $\ln(c_0/c_t)$ 随过流时间增大呈增加趋势,而 5 月份无明显变化,6 月份则呈下降趋势。1—3 月 $\ln(c_0/c_t)$ 值均大于 0,但其他月份 $\ln(c_0/c_t)$ 均出现负值的情况,主要是因为部分断面 BOD$_5$ 波动较大,超过初始断面浓度。拟

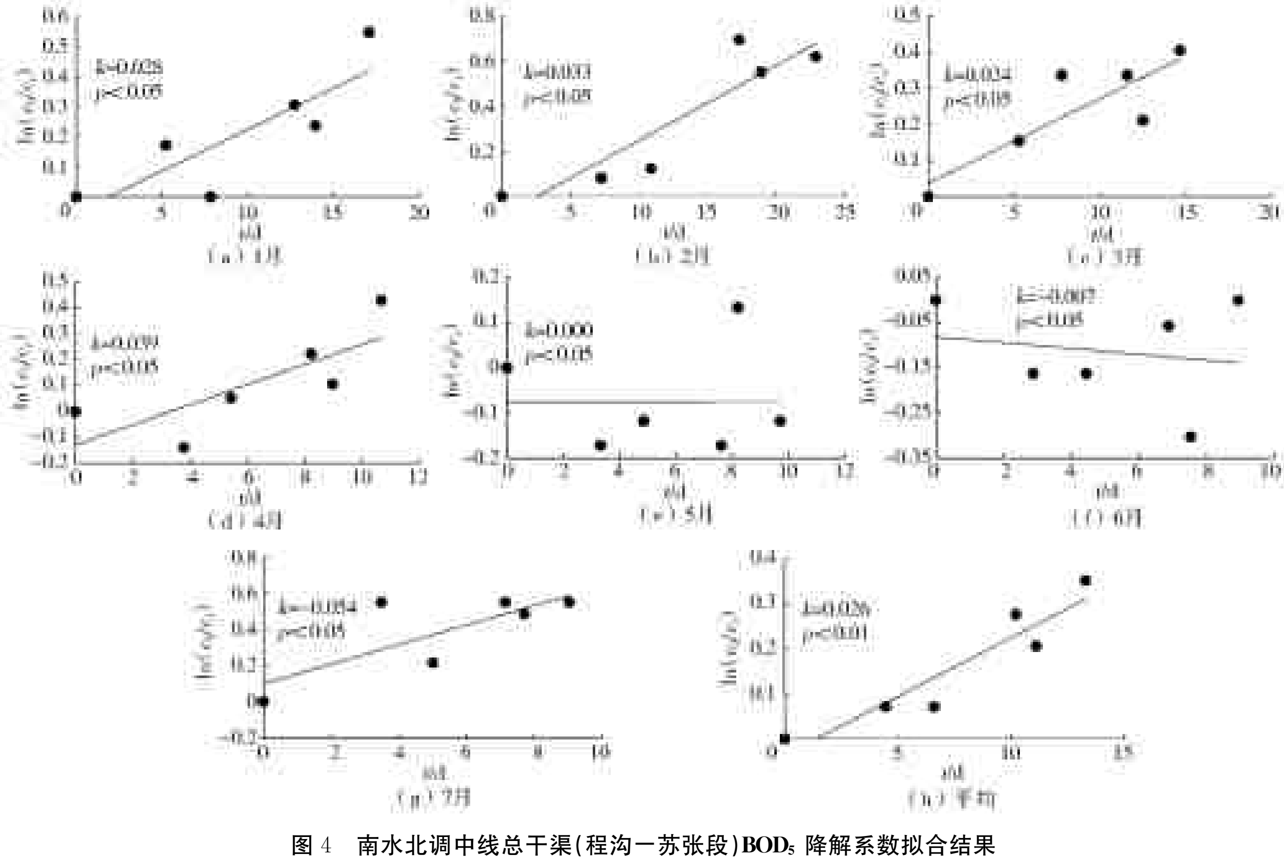


图 4　南水北调中线总干渠(程沟—苏张段)BOD$_5$ 降解系数拟合结果

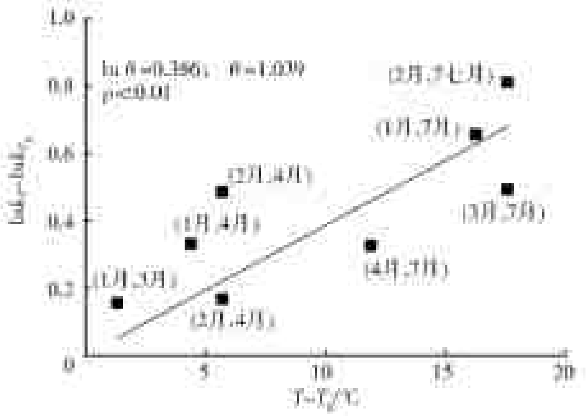
合结果显示,1—4 月及 7 月的降解系数 k 分别为 0.028($p<0.05$),0.033($p<0.05$),0.024($p<0.05$),0.039($p<0.05$),0.054($p<0.05$),均为统计显著;但 5 月、6 月的拟合 k 值均不具有统计显著性($p>0.05$)。平均值的拟合结果显示,k 值为 0.026($p<0.01$)。

2.3　温度对研究渠段 BOD_5 降解系数的影响

从各月份平均水温和 BOD_5 降解系数的对应关系看(表 2),降解系数基本随温度的升高而增大。1—3 月的平均水温为 9.5 ℃,其降解系数平均为 0.028 1/d;4 月水温升高到 14.7 ℃,其降解系数增加到 0.039 1/d;7 月水温进一步升高到 26.5 ℃,降解系数则达到 0.054 1/d。图 5 显示,通过不同月份的两两组合,平均水温差和 BOD_5 降解系数的对数差呈现出比较好的线性关系($p<0.01$),拟合斜率 $\ln\theta$ 为 0.386,计算得到温度校正系数 θ 为 1.039。

表 2　南水北调中线总干渠(程沟一苏张段)不同月份平均水温及其对应 BOD_5 降解系数

月份	1 月	2 月	3 月	4 月	7 月
平均水温/℃	10.3	9.0	9.0	14.7	26.6
BOD_5 降解系数/d^{-1}	0.028	0.033	0.024	0.039	0.054



注:(1 月,2 月)和(2 月,3 月)数据点位于坐标系其他象限,未显示。

图 5　南水北调中线总干渠(程沟一苏张段)BOD_5 降解的温度校正系数拟合结果

3　讨　论

本研究得到南水北调中线总干渠 BOD_5 降解系数在 0.024/d～0.054 1/d(5、6 月除外),该结果与其他区域的水体自净能力相比相对较小。如王平等[12]研究了汉江中下游河段的水体自净过程,计算得到 BOD_5 降解系数 0.08 1/d～0.62 1/d;张荔等[13]运用稳态一维 BOD_5 降解模型计算了陕西沿河主干河段的河流降解系数为 2.69 1/d;国外的一些天然河流的 BOD_5 降解系数也在 0.05/d～3.0 1/d[14]。南水北调中线总干渠与常规河流存在较大的不同。一方面总干渠渠底和边坡均为硬化结构,运行初期难以形成完善的附着生物和底栖生境,不利于自净能力的增强[15-16]。其次总干渠作为饮用水水源地污染物本地浓度较低,BOD_5 平均浓度在 2 mg/L左右,不利于微生物群落的快速繁殖和增长,影响有机物污染物的降解过程[17]。这些可能是总干渠水体降解系数低于其他区域的主要原因。

研究表明,温度对于水体有机物降解系数有重要的影响,常规河流 0 ℃和 30 ℃条件下降解系数能够相差 3 倍以上[18]。温度对降解系数的影响主要通过改变微生物的活性来实现。水体自净过程主要由微生物驱动,在适宜的范围内,温度升高能够加快微生物体内酶促反应速率,促进和强化微生物的生理活动,从而提高有机物降解系数[6]。很多研究对温度校正系数 θ 值进行了测定,其结果大多在1.02～1.08[19-20]。本研究计算得到 θ 值为 1.04,说明拟合结果较好反映了温度对总干渠水体自净能力的影响。

本研究采用实测数据进行拟合计算,BOD_5 的浓度变化与理想的自净衰减过程存在偏差,尤其是 5 月和 6 月的 BOD_5 降解系数拟合结果不显著,主要原因可能是沿途存在外源有机物输入。南水北调中线总干渠空虽然为全封闭设计,但作为明渠系统,渠道水体有机物除了自净衰减外,还是会受到大气干湿沉降、渠道坡面和桥面径流、闸坝水流扰动等众多因素的影响。以渠道桥面径流为例,根据刘文明等[21]的研究,公路和桥面的雨水径流 BOD_5 浓度超过 30 mg/L。在降雨强度较大的情况下,桥面雨水径流将可能使干渠局部水体的污染物浓度明显升高。另外,一些偶发性的污染源,如雨洪污水、受污染地下水等也都可能对总干渠水质产生影响[22]。本研究未得到显著拟合结果的 5 月和 6 月恰好处于雨季,根据南阳市 2015 年气象资料,5 月和 6 月均有 15 d 降雨,且部分时段出现大雨和暴雨,而 7 月仅为 8 d 降雨,多为小雨。坡面汇入的径流可能形成有机物的输入源,将导致 BOD_5 浓度沿途波动,影响 BOD_5 降解系数的拟合结果。

4　结　论

(1)研究渠段 BOD_5 降解系数 k 数值范围为 0.024～0.054 1/d,与其他区域相比,总干渠的水体自净能力相对较小。

(2)研究渠段 BOD_5 降解系数季节变化明显，1—3 月、7 月的拟合 k 值分别为 0.028 1/d($p<0.05$)，0.033 1/d($p<0.05$)，0.024 1/d($p<0.05$)，0.039 1/d($p<0.05$)，0.054($p<0.05$) 1/d；5 月、6 月的拟合 k 值分别为 0 和 −0.007 1/d，均不具有统计显著性($p>0.05$)。

(3)研究渠段 BOD_5 降解系数受温度影响显著，基本随温度的升高而增大，温度校正系数 θ 值为 1.039。

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Study on water self-purification capacity in a typical section of middle route in the main channel of South-to-North Water Transfer Project

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Abstract: Self-purification ability of the water body is an important factor affecting the change in water quality indicators. In this study, the self-purification capability was characterized by the BOD_5 degradation coefficient. From January 2015 to July 2015, six monitoring sections (Chenggou, Fangcheng, Shahenan, Lanhebei, Xinfeng, and Suzhang) of the main canal in the middle route of the south to North Water Transfer Project were selected to monitor the BOD_5 monthly data and to study the flow and water depth of each control gate in the canal section, the one-dimensional steady BOD_5 degradation model was used to fit the BOD_5 degradation coefficient of the main channel. The results showed that the degradation coefficients of BOD_5 in the channel section between 0.024/d～0.054/d. The capacity of water self-purification of the main channel is relatively small compared to other areas. The seasonal change of the BOD_5 degradation coefficient in the channel section was obvious. The fitting k values from January to April and July were 0.028/d ($p<0.05$), 0.033/d ($p<0.05$), 0.024/d ($p<0.05$), 0.039/d($p<0.05$), 0.054/d($p<0.05$), respectively. But the fitting k values of May and June were not statistically significant ($p>0.05$). The runoff from the bridge and the road formed the input of exogenous organic pollution may be the main cause behind this insignificant fluctuation of BOD_5 concentration in the channel. The self-purification ability of the main channel was significantly affected by temperature. The degradation coefficient of BOD_5 increased with the increase of temperature and the temperature correction coefficient was 1.039, respectively.

Key words: self-purification ability; South-to-North Diversion Project; main channel of the Middle Route; BOD_5; degradation coefficient

The Middle Route of South-to-North Water Transfer Project is an important strategic water resource allocation project in China. After the project is opened to water, it brings huge social, economic and ecological benefits to the society along the route and guarantees the normal social and economic development of the provinces and cities along the route. However, since the operation of the mid-line project, the water quality assurance of water delivery is facing a huge challenge due to the

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complex structure of the main canal, the large spatial span, and the unique type of ecosystem. The total length of the main canal in the middle route of the South-to-North Water Transfer Project is 1 432 km. The long-distance water transport makes the factors affecting water quality complex and diverse, such as the self-purification factor of the water body of the canal itself, the atmospheric dry and wet settlement outside the canal, rainwater runoff on the bridge and slope, etc. Studying the self-purification ability of water bodies is of great significance for understanding the trend of water quality in the main canal and summarizing the change law.

The degradation coefficient of organic matter is an important indicator to assess the self-purification ability of water[1]. Many studies have obtained the size of the degradation coefficient through the measurement and simulation of the degradation process of organic matter. For example, Cai Jiannan et al.[2] estimated the BOD_5 (five-day biochemical oxygen demand) degradation coefficient of the study section based on a steady-state one-dimensional BOD_5 degradation model. Mu Jinbo et al.[3] assessed the BOD_5 degradation coefficient of the Nansi Lake and the river entering lake using the least square method based on the indoor experimental research. Li Junbin[4] calculated the degradation coefficients of major pollutants including BOD_5 in Zhangze Reservoir based on a statistical analysis of water quality monitoring data. Liu Hongliang et al.[5] obtained the concentration-time process line through the monitoring of the tracer to obtain the BOD_5 degradation coefficient. Several other scholars used the existing research results to carry out an analogy analysis with the actual situation of the research river to determine the BOD_5 degradation coefficient[6]. In recent years, some key influencing factors on the self-purification capacity of rivers and lakes, such as the increase of temperature due to climate change[7], and the discharge of sewage and wastewater[8-9] have gradually attracted attention.

At present, there has been a lot of research results on the self-purification capacity of natural rivers, but there is still a lack of in-depth understanding of the self-purification capacity of large-scale artificial water transfer channels as the main channel of the middle route of the South-to-North Water Transfer Project. Compared with natural rivers, artificial water transport channels usually have the characteristics of a single habitat structure, uniform water flow, and high degree of artificial regulation[10], and their self-purification ability may be significantly different from natural rivers. Therefore, based on the BOD_5 monitoring data of the main canal in the middle route of the South-to-North Water Diversion Project, this paper calculates the BOD_5 degradation coefficient of the main canal through statistical analysis of water quality monitoring data and provides a reference for understanding the self-purification capacity of the main channel.

1 Data and methods

1.1 Basic data

Six monitoring sections (Chenggou, Fangcheng, Shahenan, Lanhebei, Xinfeng, and Suzhang) of the main channel in the middle route of the South-to-North Water Transfer Project were selected for the section distribution, BOD_5 and water temperature data from January 2015 to July 2015. The water temperature monitoring data and monitoring section distribution are shown in Fig. 1. The determination of BOD_5 adopts the national standard method (GB 7488-87) stipulated in " Quality Standard for Surface Water Environment" (GB 3838-2002). There are 13 sluice gates in the study channel section, and there may be differences in flow velocity between the sluice gates. In order to calculate the channel velocity and flow time, the monthly averages of the discharges of the various sluice in the channel section (Chenggou-Suzhang section) were collected and sorted. The parameters of the channel slope coefficient and the width of the canal bottom between adjacent sluice gates are shown in Tab. 1.

1.2 Calculation method of BOD_5 degradation coefficient

1.2.1 BOD_5 degradation coefficient fitting model

The degradation coefficient was determined

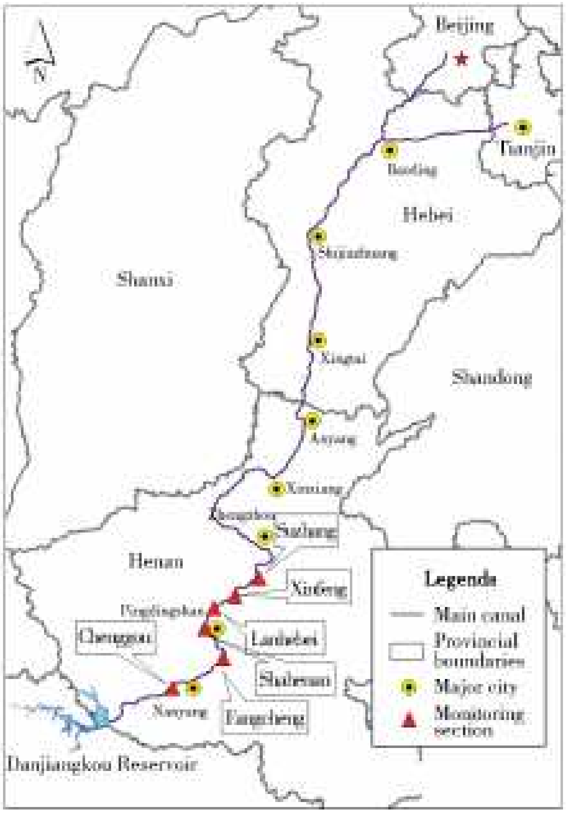


Fig. 1　Distribution and location of water quality monitoring sites of the studied section in the middle route main channel of the South-to-North Water Diversion Project

using the steady-state one-dimensional BOD_5 degradation model[11] as formula(1)

$$c_t = c_0 \cdot \exp(-kt) \tag{1}$$

where c_t is the concentration of BOD_5 (mg/L) at time t; c_0 is the initial concentration of BOD_5 (mg/L); k is the degradation coefficient of BOD_5 (1/d); t is the overcurrent time (d).

From equation (1)

$$\ln\left(\frac{c_0}{c_t}\right) = kt \tag{2}$$

According to equation (2), ln (c_0/c_t) and t have a linear relationship. Based on the BOD_5 values of the six monitoring sections, calculate the degradation time t and ln (c_0/c_t) between the initial section and each section, and plot ln (c_0/c_t)~t scatter. Linear regression is performed on the scattered points to obtain the degradation equation, and the slope can be observed as the BOD_5 degradation coefficient of the main trunk canal. Both scatter plots and linear regression analyses were performed in SPSS18. 0.

Tab. 1　The monitoring section and control gate of the studied channel section

Monitoring section	Control/Sluice gate	Distance from canal head/km	Average flow from January to July/($m^3 \cdot s^{-1}$)	other parameters
Chenggou		93		Included: (1) Monthly average flow (2) Monthly average water depth in front of the sluice (3) Monthly average water depth behind the sluice (4) Channel slope coefficient between two adjacent sluice gates (5) Width of channel bottom
	Shierli River control gate	97	53. 507	
	Bai River control gate	116	52. 785	
	Dongzhao River control gate	137	52. 095	
	Huangjin River control gate	159	52. 264	
	Caodun River control gate	181	53. 108	
Fangcheng		195		
	Li River control gate	209	50. 480	
	Peng River control gate	232	52. 356	
Shahenan		238		
	Sha River control gate	241	49. 480	
	Yudai River control gate	266	50. 053	
	Beiru River control gate	279	50. 477	
	Lanhebei Lan River control gate	300	49. 134	
Xinfeng		315		
	Ying river control gate	327	52. 058	
	Xiaohong River control gate	348	47. 955	
Suzhang		354		

1. 2. 2　Calculation method of overcurrent time

In order to accurately calculate the flow time of water bodies between different sections, the velocity distribution of the channel section is studied.

The velocity between the two adjacent brake sections is relatively uniform, and the calculation method of the average velocity is as formula (3)

$$\begin{cases} h=\frac{1}{2}(h_1+h_2) \\ A=(b+mh)h \\ v=q/A \end{cases} \tag{3}$$

Where: h is the average water depth between two adjacent sluice gates: measured in (m); h_1 is the water depth behind the former sluice gate: measured in (m); h_2 is the water depth before the gate of the next control gate: measured in (m); A is the cross-sectional area of water flow: measured in (m^2); B is the width of canal bottom: measured in (m); m is the slope coefficient; q is the flow (m^3/s); v (m/s) is the average flow velocity between two adjacent sluice gates.

The overcurrent time between two adjacent sluice gates is calculated according to equation (4)

$$t=\frac{S}{v}\times\frac{1}{3600\times 24} \tag{4}$$

where t is the flow passage time (d) between two adjacent sluice gates; S is the distance (m) between two adjacent sluice gates; v is the average flow velocity (m/s) between two adjacent sluice gates.

1.3 Analyze the influence of temperature on BOD_5 degradation coefficient

Temperature is the most basic factor affecting the self-purification capacity of the water body. The main channel of the middle route of the South-to-North Water Transfer Project is located in the north of China, and the temperature difference between different months is obvious, so this study focuses on the influence of temperature on the BOD_5 degradation coefficient. Generally, the influence of temperature on the degradation coefficient can be characterized by the temperature correction coefficient[6], as shown in formula (5)

$$k_{\mathrm{T}}=k_{T_0}\theta^{(T-T_0)} \tag{5}$$

where k_T is the degradation coefficient (1/d) corresponding to temperature T; k_{T_0} is the degradation coefficient (1/d) corresponding to temperature T_0; T, T_0 is the temperature (℃); θ is the temperature correction coefficient.

By taking the logarithm of both sides of formula (5)

$$\ln k_T-\ln k_{T_0}=(T-T_0)\ln\theta \tag{6}$$

It can be seen from equation (6) that $\ln k_T-\ln k_{T_0}$ is directly proportional to $T-T_0$, and the proportion coefficient is $\ln\theta$. Based on the calculated BOD_5 degradation coefficient and its corresponding average water temperature in different months, the ($\ln k_T-\ln k_{T_0}$)~($T-T_0$) scatter diagram is drawn by combining two different months. The temperature correction coefficient θ can be calculated by linear regression of scattered points and its slope is $\ln\theta$. A scatter plot and linear regression analysis were performed in SPSS18.0 software.

2 Results and analysis

2.1 Study on the variation of BOD_5 concentration and water temperature in the canal section

The variation trend of BOD_5 and water temperature is shown in Fig. 2. BOD_5 generally shows a downward trend along the way, but the law of time change is not obvious. The average value of Chenggou section is 2.1 mg/L, Fangcheng and Shanhenan section is 1.9 mg/L, the average value of Lanhebei section is further reduced to 1.6 mg/L, the average value of Xinfeng section is increased to 1.7 mg/L, and the average value of Suzhang section is further reduced to 1.5 mg/L, respectively. At the time scale, the highest BOD_5 of Chenggou section is 2.6 mg/L in February and July, the lowest is 1.6 mg/L in May, and it gradually declines from February to May. The highest BOD_5 of the Fangcheng section is 2.4 mg/L in February, the lowest is 1.5 mg/L in July. The highest BOD_5 of the Shahenan section is 2.4 mg/L in February, the lowest is 1.5 mg/L in March. The highest BOD_5 of the Lanhebei section is 1.9 mg/L in May, and the lowest is 1.3 mg/L in February 1.3 mg/L gradually increased from February to May. The highest value of the Xinfeng section was 2.3 mg/L in June and the lowest value was 1.4 mg/L in May. The highest value of the Suzhang section was 1.8 mg/L in May and the lowest value was 1.1 mg/L in January.

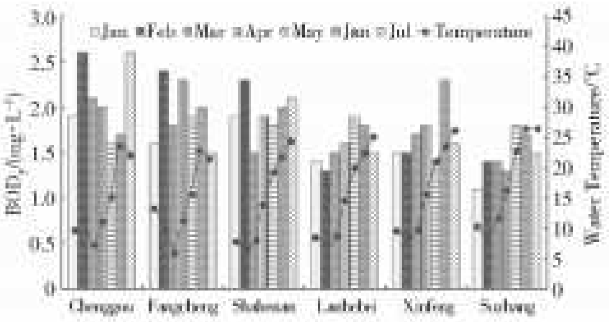


Fig. 2　BOD_5 and water temperature variation along the main channel (Chenggou-Suzhang)

The water temperature shows obvious temporal change, and the difference between sections are relatively small. The water temperature of each section is basically between 8～28 ℃. The lowest temperature of the Chenggou section is 8.4 ℃ in March and 27.1 ℃ in June. The lowest temperature of the Fangcheng section is 7.9 ℃ in March and 27.5 ℃ in June. The lowest temperature of the Shahenan section is 6.6 ℃ in February and 26.8 ℃ in July while the lowest temperature of the Lanhebei section is 6.7 ℃ in February and 26.9 ℃ in July. On the other hand, the lowest temperature of the Xinfeng section is 7.0 ℃ in February and 27.1 ℃ in July. The Suzhang section has a minimum temperature of 7.3 ℃ in February and maximum temperature 27.3 ℃ in July. The water temperature is relatively low from January to March, while there is a significant rise in water temperature from March to July.

2.2　Calculation results of BOD_5 degradation coefficient in the selected study channel section

2.2.1　Distribution of velocity and flow time

The calculation results of the flow velocity and overcurrent time are shown in Fig. 3. The downward trend of the flow velocity from January to March is obvious. The highest flow velocity in January is 0.25 m/s and the lowest is 0.14 m/s. The highest flow velocity in February is 0.18 m/s. and the lowest is 0.11 m/s. The highest velocity in March is 0.25 m/s, and the lowest is 0.18 m/s. The average velocity increased significantly from April to July, but fluctuated greatly, with a maximum of 0.34 m/s and a minimum of 0.23 m/s in April. A maximum of 0.29 m/s and a minimum of 0.24 m/s in May. Whereas a maximum of 0.46 m/s in June, the lowest is 0.27 m/s. Overall, the highest in July is 0.39 m/s, and the lowest is 0.30 m/s. On average , the velocity of the main canal is generally

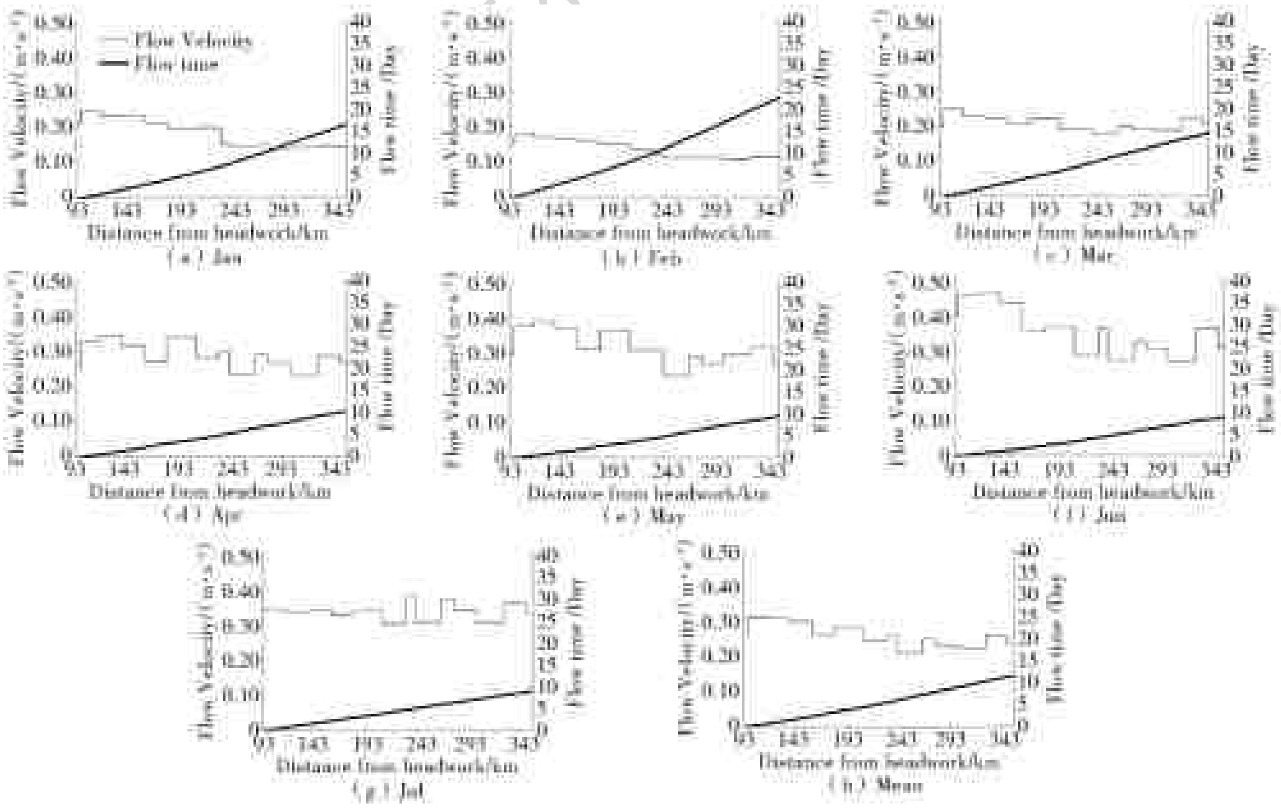


Fig. 3　Flow velocity distribution and crossing time along the main channel (Chenggou-Suzhang)

decreasing along the course, with an average velocity of 0.26 m/s.

Taking the Chenggou section as the starting point, the flow passage time is inversely proportional to the velocity along the channel. The flow velocity was the slowest in February, 22 days in January, 14.1 days in March, and 9 days in April to July. According to the average flow rate, the time of overflow is 11.3 d.

2.2.2 Fitting results of BOD_5 degradation coefficient

Regression fitting was performed on the average degradation coefficients from January to July and the other remaining months. The scatter distribution and fitting results are shown in Fig. 4. The scatter plot shows that from January to April, July and the average value $\ln(c_0/c_t)$ increases with the increase of the overcurrent time, but there is no significant change in May, and it shows a downward trend in June. From January to March, the values of $\ln(c_0/c_t)$ were all greater than 0, but the values of $\ln(c_0/c_t)$ were negative in other months, mainly because the BOD_5 of some sections fluctuated greatly and exceeded the initial section concentration. The fitting results show that the degradation coefficients k from January to April and July are 0.028 ($p<0.05$), 0.033 ($p<0.05$), 0.024 ($p<0.05$), 0.039 ($p<0.05$), and 0.054 ($p<0.05$), respectively, but the fitted k values in May and June are not statistically significant ($p>0.05$). The fitted result of the average value shows that the k value is 0.026 ($p<0.01$).

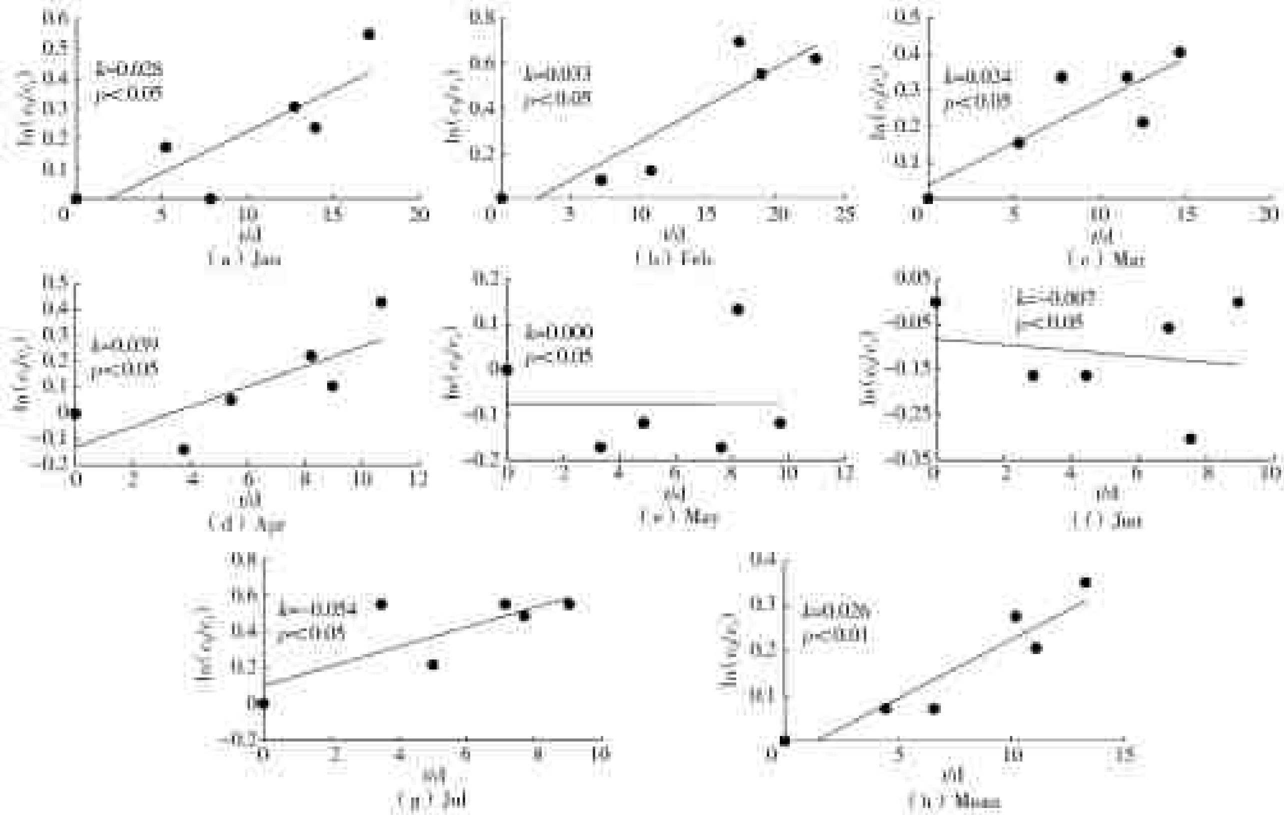


Fig. 4 BOD_5 degradation coefficient fitting results along the main channel (Chenggou-Suzhang)

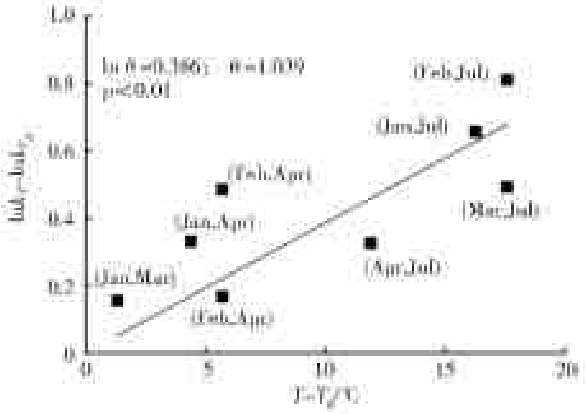
2.3 Effect of temperature on BOD_5 degradation coefficient

According to the corresponding relationship between average water temperature and BOD_5 degradation coefficient in each month (Tab. 2), the degradation coefficient increases with the increase of temperature. From January to March, the average water temperature is 9.5 ℃, and the average degradation coefficient is 0.028 1/d. In April, the water temperature rises to 14.7 ℃ and the degradation coefficient increases to 0.039 1/d, while in July, the water temperature further rises to 26.5 ℃, and the degradation coefficient reaches 0.054 1/d. Fig. 5 shows that through the pairwise combination of different months, the logarithm difference of average water temperature difference and BOD_5

degradation coefficient shows a good linear relationship ($P<0.01$), the fitting slope $\ln\theta$ is 0.386, and the calculated temperature correction coefficient θ is 1.039.

Tab. 2　Average water temperature in different months and corresponding BOD_5 degradation coefficient along the main channel (Chenggou-Suzhang)

Month	1	2	3	4	7
Average water temperature/℃	10.3	9.0	9.0	14.7	26.6
BOD_5 degradation coefficient/d^{-1}	0.028	0.033	0.024	0.039	0.054



Note: (Jan, Feb) and (Feb, Mar) data points are located in other quadrants of the coordinate system, not shown.

Fig. 5　Fitting results of the temperature correction factor for BOD_5 degradation along the main channel (Chenggou-Suzhang)

3　Discussion

In this study, the BOD_5 degradation coefficient of the main channel in the middle route of the South-to-North Water Transfer Project is between 0.024 1/d and 0.054 1/d (except for May and June), which is relatively small compared with the self-purification capacity of other areas. For example, Wang Ping et al.[12] studied the water self-purification process in the middle and lower reaches of the Han River and calculated the BOD_5 degradation coefficient between 0.08 and 0.62 1/d. Zhang Li et al.[13] calculated the river degradation coefficient of the main reaches along the river in Shaanxi by using the steady-state one-dimensional BOD_5 degradation model, and the BOD_5 degradation coefficient of some natural rivers in foreign countries was also between 0.05 and 3.00 1/d[14]. The main channel of the middle route of the south to the North Water Transfer Project is quite different from the conventional river. On the one hand, the bottom and slope of the main canal are all hardened structures, therefore, it is difficult to form a perfect attached organism and benthic habitat at the initial stage of operation, which is not conducive to the enhancement of self-purification capacity[15-16]. Secondly, the local concentration of pollutants in the main channel as the drinking water source is relatively low, and the average concentration of BOD_5 is about 2 mg/L, which is not conducive to the rapid propagation and growth of the microbial community and affects the degradation process of organic pollutants[17]. These may be the main reason why the degradation coefficient of the main channel is lower than that of other areas.

Studies have shown that temperature has an important effect on the degradation coefficient of water organic matter, and the degradation coefficients of conventional rivers at 0 ℃ and 30 ℃ can differ by more than three times[18]. The effect of temperature on the degradation coefficient is mainly achieved by changing the activity of microorganisms. The self-purification process of water is mainly driven by microorganisms. Within a suitable range, an increase of temperature can accelerate the rate of enzymatic reactions in the microorganisms, promote and strengthen the physiological activities of microorganisms, and thereby increase the degradation coefficient of organic matter[6]. Many studies have measured the temperature correction coefficient θ, and the results are mostly between 1.02 and 1.08[19-20]. The calculated value of θ in this study is 1.04, which indicates that the fitting result better reflects the influence of temperature on the self-purification capacity of the main canal.

In this study, the measured data were used for fitting calculations. The concentration of BOD_5 changed from the ideal self-purification attenuation process, especially the fitting results of the BOD_5 degradation coefficients in May and June were not significant. The main reason may be the existence of external organic matter input along the way. Although the main canal space of the middle route of the South-to-North Water Transfer Project is fully enclosed, as an open channel system, the organic matter in the channel water body is not only self-purification attenuation, but also affected by many factors such as the atmospheric dry and wet settlement, the runoff of the channel slope and the bridge deck, the flow disturbance of the gated dam and so on. Taking the canal bridge runoff as an example, according to the study of Liu Wenming et al. [21], the concentration of BOD_5 in rainwater runoff on highways and bridge decks exceeds 30 mg/L. Under the condition of heavy rainfall, the rainwater runoff from the bridge deck may increase the concentration of pollutants in the main body of the canal. In addition, some occasional pollution sources, such as rainwater, polluted groundwater, etc, may also affect the water quality of the main canal[22]. May and June, in which no significant fitting results were obtained in this study, coinciding with the rainy season. According to the 2015 meteorological data of Nanyang City, there were 15 days of rain in May and June, with heavy rain in some periods, while in July only 8 days of rainfall which were mostly light rain. The runoff may form an input source of organic matter, which will cause the BOD_5 concentration to fluctuate along the way and affect the fitting result of the BOD_5 degradation coefficient.

4 Conclusions

(1) The value range of BOD_5 degradation coefficient k is 0.024-0.054 1/d. Compared with other areas, the water self-purification capacity of the main channel is relatively small.

(2) The results showed that the seasonal variation of BOD_5 degradation coefficient was obvious, the fitting k values from January to March and July were 0.028 ($p<0.05$), 0.033 ($p<0.05$), 0.024 ($p<0.05$), 0.039 ($p<0.05$), 0.054 ($p<0.05$) 1/d, respectively, and the fitting k values in May and June were 0 and -0.007/d, respectively, which were not statistically significant ($p>0.05$).

(3) The degradation coefficient of BOD_5 was significantly affected by temperature and increased with the increase of temperature. The temperature correction coefficient θ was 1.039.

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