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不同流速下湖泊水体重金属含量垂向分布特征

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摘要:在室内水槽试验中模拟了沉积物的运动特征,通过不同流速、不同水深处重金属总含量以及溶解态重金属含量的试验测定,得到了不同流速、不同水深处 Cu、Zn、Pb 重金属含量和与沉积物距离的基本关系式。结果表明,水动力作用较强时,水体中溶解态 Cu、Zn、Pb 含量从底层水体至表层水体呈对数增长;鄱阳湖野外实测试验表明,不同流速、不同水深处 Cu、Zn、Pb 溶解态含量实测值与计算值的相对误差在 ±15% 范围内,说明本试验装置操作性较强,所建关系式基本合理。

关键词:重金属;水槽;沉积物;流速;垂向分布特征;鄱阳湖

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Vertical Distribution Characteristics of Heavy Metals in Lake under Different Hydrodynamic Conditions

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Abstract: The movement of lake sediments under different hydrodynamic conditions was simulated, and vertical distribution characteristics of heavy metals in lake under different hydrodynamic conditions were explored with self-designed circulating flume and sediments sampled from Xingzi section of Poyang Lake. The flume device was composed of inlet tank (0.5 m^3), test area (2 m in length, 1 m in width, and 0.5 m in height), outlet tank (0.5 m^3), storage tank (1 m^3) and pump (maximum flow rate of 100 m^3/h). Prior to testing, sediment was spread at the flume bottom, and lightly pressed and flattened to a thickness of 8 cm. After remaining it untouched for 0.5 h, water was added into the device. Water depth in the flume was controlled at 140 cm. Water was pumped from the storage tank into the inlet tank, and flowed through the test area, the outlet tank and eventually returned to the tank. During the test, the flow rate in the flume was gradually increased from 0 cm/s, and its flow rate was set through the control of the gate as 0 cm/s, 5 cm/s, 15 cm/s, 25 cm/s, 35 cm/s, 45 cm/s and 65 cm/s. To ensure that the water flowed through the flume at least once, the testing period was maintained 1 h under each flow rate, and then immediately proceeded to the next flow rate until it reached the maximum flow rate. During the test, the incipient motion characteristics of sediment, including critical motion state, slight motion state and plenty motion state, were initially simulated. The water depth in the flume was divided into four layers. The total heavy metal concentration and dissolved heavy metal concentration were measured at different flow

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rates and different water depths. In order to minimize deviation, heavy metal concentration was measured three times and the average value was taken under each group of water flow and water depth condition. When the sediment was in critical motion state at flow rate of less than 25 cm/s, a diluted suspension at the sediment surface was appeared with the increase of flow rate. The total heavy metal concentrations were similar at different water depths in this period. When the sediment was in slight motion state at flow rate of 25 cm/s to 50 cm/s, water became turbid, with part of the sediment washed up. Shear stress at sediment surface was obviously larger than that in critical motion state, and the total heavy metal concentrations were increased from water surface to bottom, although it was not obvious. When the sediment was in plenty motion state at flow rate of 60 cm/s to 70 cm/s, a large amount of sediment was washed up, and water became turbid in a short period. Large quantities of heavy metals in the sediment were released into water, and the total heavy metal concentration was increased obviously along the water depth direction. In addition, by analyzing the concentrations of dissolved Cu, Zn, Cd and Pb in each layer with curve fitting method, vertical distribution characteristics of heavy metals under different hydrodynamic conditions were revealed. The basic formula was established between heavy metal concentration and height above sediment surface. The results showed that when the hydrodynamic condition was strong, the concentrations of dissolved Cu, Zn, Pb were increased logarithmically from water bottom to water surface. Furthermore, to detect the applicability of the established formula, the testing results were applied to measurement of Poyang Lake, water samples collected from Poyang Lake Bridge section and Xingzi section at 0.3 m, 0.8 m, 1.3 m and 1.8 m above sediment were used to measure the dissolved heavy metal concentration. Flow rate at the two sections were 39 cm/s, 75 cm/s and 44 cm/s, 68 cm/s, respectively, when the samples were collected. By substituting the measured data into the established formula, the obtained result showed that the relative error between calculation results and measured results was within ±15%. The formula was applicable at flow rate of 65 cm/s to 75 cm/s in lakes with sediment grain size of 50 μm to 200 μm. The established formula was basically reasonable. The device was feasible for the experiment with strong operability. The research results could provide references for revealing heavy metal release characteristics under different water conditions.

Key words: heavy metals; flume; sediment; flow rates; vertical distribution characteristics; Poyang Lake

引言

风浪作用会造成水体的紊流扩散[1],继而水体与底泥产生强烈的交换[2]。一般沉积物中重金属含量能反映出水体重金属污染状况[3],而当环境条件改变时,会造成重金属的重新释放[4],释放之后会通过生物富集等作用直接或间接危害水生态系统[5],

释放量的多少与风浪作用下沉积物的再悬浮和沉降有关[6]。沉积物在悬浮沉降过程中,颗粒物会携带大量的其他物质一起发生变化[7],因此研究水体重金属元素垂向分布特征是探讨水体重金属迁移转化规律的前提和基础,也是研究湖泊重金属污染的关键问题。目前,对湖泊重金属的研究大多集中在沉积物上[8-9],而沉积物重金属的分布更多反映的是历史污染的记录[10-13],对于不同流速下水体重金属垂向分布特征却少有报道和研究。

本文通过室内水槽试验分析了不同流速下水体重金属垂向分布特征,探讨水体重金属含量垂向迁移转化规律,并将试验结果应用于鄱阳湖野外实测试验中,以期检测本文结论的适用性。

1 试验材料与方法

1.1 试验装置

水槽装置如图1所示。装置由水箱、水泵和流量计组成,水箱Ⅰ(储水箱)体积为3 m^3,上部水槽长2 m、宽1 m、高1.5 m,水泵最大流量为100 m^3/h,

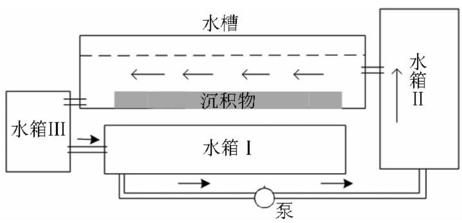

图1 试验装置

Fig.1 Experiment device

泵后安装流量计,试验时通过调节水槽出水口的叶栅式尾门与水泵闸门,保证水槽内水位稳定和水槽内水体流速。

采用除氯自来水作为试验用水,选取鄱阳湖星子段沉积物为试验沉积物,沉积物中 Cu、Zn、Cd、Pb 初始值分别为 34.84、104.50、0.58、43.50 mg/kg。试验开始前在水槽中平铺沉积物后轻压至厚 8 cm,然后静置 0.5 h,继而水箱和水槽中全部充满水,水槽内水深控制在 140 cm,静置 24 h 后开始试验,试验时通过调节泵及水槽出水口门栅控制水槽试验用水流速分别为 0、5、15、25、35、45、65 cm/s,试验流速从零开始逐渐加大直至最高流速,为保证试验水至少流经水槽 1 次,各流速均保持 1 h。

1.2　取样方法与分析

1.2.1　取样方法

将水槽内水深等分为 4 层,试验时,各流速下均由 4 名试验人员采用矿泉水瓶同步采集各层水样,采样瓶放入不同水深水体后均稳定 5 min 后取出,为减少误差,每一层均平行采样 3 次(平行采样均待上次采样结束后 5 min 进行),即各流速下需采集水样 12 个,采样时同时记录采样点的水深。采样前采水器先用自来水清洗一次,再用试验水清洗几次,采集到的水样分为原水和过滤水,原水是没有经过任何处理的水,过滤水是经过孔径为 0.45 μm 尼龙滤膜过滤后水样。留在滤膜上的则为悬浮态,经过 0.45 μm 滤膜滤后水样含有溶解态重金属,分别测原水、过滤水重金属含量,则水样中悬浮态、溶解态重金属含量以及总重金属含量均可测出。

1.2.2　分析项目与方法

选取 Cu、Zn、Cd、Pb 作为分析项目,选用 ICP - MS 法测定其含量,每次取样时水样采集 1 000 mL 后加入 10 mL 硝酸(浓硝酸与蒸馏水体积比为 1)进行酸化处理,样品检测操作严格按照《水和废水监测分析方法》[14](第 4 版)。

2　结果与分析

2.1　试验分析

由相关文献可知[15-18],泥沙的起动分为将动未动(流速为 0 ~ 25 cm/s)、少量动(流速为 25 ~ 50 cm/s)、普遍动(60 ~ 70 cm/s)3 种状态,本次试验沉积物运动特征与此运动状态较为吻合,不同流速、不同水深下各重金属元素含量见表 1,不同流速下总重金属含量垂向分布趋势见图 2。当流速为 5、15 cm/s 时不同水深处重金属含量与静水下含量差异不大,流速为 35 cm/s 时各重金属含量变化规律与 45 cm/s 类似,故未进行分析。

表 1　不同流速、不同水深(水体与沉积物的距离)下重金属各形态含量

Tab.1　Content of heavy metals at different flow velocities and different water depths

流速/(cm·s^{-1})	水深/cm	Cu/(μg·L^{-1})			Zn/(μg·L^{-1})			Pb/(μg·L^{-1})			Cd/(μg·L^{-1})		
		总含量	溶解态	悬浮态	总含量	溶解态	悬浮态	总含量	溶解态	悬浮态	总含量	溶解态	悬浮态
0	125	35.20	26.90	8.30	52.60	40.90	11.70	4.46	3.94	0.52	1.03	0.77	0.26
	90	36.70	27.20	9.50	53.20	41.30	11.90	4.40	3.98	0.42	1.08	0.80	0.28
	55	34.60	27.30	7.30	52.30	40.20	12.10	4.45	3.92	0.53	1.06	0.79	0.27
	20	36.20	26.40	9.80	53.50	40.90	12.60	4.43	3.95	0.48	1.09	0.82	0.27
25	125	37.30	27.80	9.50	53.40	39.60	13.80	4.53	3.26	1.27	1.12	0.84	0.28
	90	36.80	28.40	8.40	54.10	40.50	13.60	4.59	3.43	1.16	1.09	0.80	0.29
	55	38.70	27.90	10.80	56.90	40.20	16.70	4.52	3.61	0.91	1.16	0.82	0.34
	20	39.40	26.80	12.60	58.20	41.80	16.40	4.73	3.12	1.61	1.18	0.86	0.32
45	125	43.60	30.90	14.00	62.40	36.90	19.70	4.63	3.37	1.26	1.28	0.97	0.31
	90	44.90	30.50	15.50	62.80	36.60	20.90	4.78	3.32	1.36	1.32	0.98	0.34
	55	47.30	29.80	19.50	68.30	35.80	27.50	4.86	3.21	1.65	1.36	0.98	0.38
	20	52.40	26.60	24.80	76.90	30.70	36.60	5.12	2.95	2.09	1.57	1.23	0.34
65	125	37.30	28.50	15.90	73.80	42.90	30.90	6.93	6.05	1.35	1.49	1.12	0.37
	90	49.20	27.60	22.90	75.20	39.80	35.40	7.17	5.89	1.71	1.56	1.21	0.35
	55	54.60	24.40	31.10	89.30	34.60	53.70	7.67	5.57	2.85	1.73	1.47	0.26
	20	65.80	16.20	48.60	117.40	21.70	95.70	8.48	4.93	4.72	2.18	2.10	0.28

2.2　结果分析

根据泥沙启动理论[16,18],当水体流速小于 25 cm/s,淤泥处于“将动未动”状态时,随流速从零逐渐增大,沉积物表面由静止逐渐悬浮一层较薄的稀释悬扬;流速介于 25 ~ 50 cm/s 之间时,淤泥处于“少量动”状态,此时水体呈浑浊状态,水槽中部分沉积物被冲起,沉积物表面所受剪切力较上一状态明显增大;流速介于 60 ~ 70 cm/s 之间时,淤泥处于

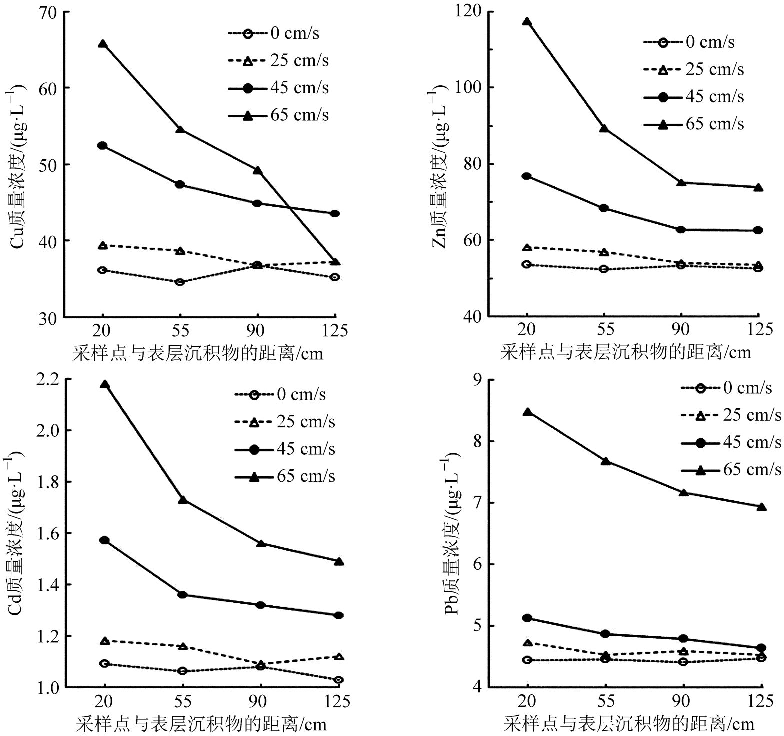

图2 不同流速、不同水深处各重金属总含量

Fig. 2 Total content of heavy metals in different water depths under different flow velocities

"普遍动"状态,水槽中沉积物被大片掀起,水体在较短的时间内呈浑浊状态,本试验现象与此规律较为吻合。

当流速为 0~25 cm/s 时,不同水深处各重金属含量差异性不大,说明弱水动力下未引起水质的波动。当流速为 25~45 cm/s 时,中上层水深处各重金属含量差异不明显,而中下层 Cu、Zn、Cd、Pb 总重金属含量略有增长,尤以最底层增长较为明显,说明中水动力下引起了沉积物中重金属的释放,此时各元素溶解态含量随水深的增大而下降,推测水动力引起沉积物中重金属的释放,故重金属总含量略有增长,同时部分沉积物进入上覆水体中,而沉积物会吸附水体中的溶解态重金属,导致水体中溶解态重金属含量减小,由于水动力不强,沉积物主要在下层水体悬浮,故只引起底部水体溶解态重金属含量减少;当流速达到 65 cm/s 时,中下层水体重金属总含量相比上层水体增大较为明显,越靠近沉积物处重金属总含量增加幅度越大,而越靠近沉积物处 Cu、Zn、Pb 溶解态重金属含量相比上层水体却明显下降, Cd 溶解态含量呈上升趋势,这可能是由于强水动力下引起了沉积物中总重金属的释放,而此流速对应的水动力强度上浮的沉积物主要还是悬浮在中下层水体中,越靠近底泥处水体中悬浮的沉积物越多,重金属总含量垂向差异较为明显,说明此时重金属在垂向的迁移及扩散作用不明显,而下层 Cu、Zn、Pb 溶解态含量下降,说明水体中悬浮的沉积物越多对水体中 Cu、Zn、Pb 溶解态吸附越强,同时也说明水动力下沉积物中 Cu、Zn、Pb 主要是以悬浮态释放,下层 Cd 溶解态含量上升说明水动力下沉积物中 Cd 主要以溶解态释放,释放量大于悬浮态的沉积物对水体中溶解态 Cd 的吸附量。

2.3 不同水深处溶解态重金属含量与水动力强度的关系

动水条件下,沉积物中溶解态以及悬浮态重金属均会释放[6],水动力作用越强,释放量越大[9],而水动力扰动导致水体中含有大量的悬浮颗粒,悬浮颗粒会再次吸收水体中溶解态重金属[11],为了找到不同流速下水体中溶解态 Cu、Zn、Pb 垂向分布规律,对各层溶解态重金属含量进行线性拟合,结果如图3所示。

从图3可知,随试验流速的增大,越靠近底泥处 Cu、Zn、Pb 溶解态含量越少,其含量随距底泥距离的加大呈对数增长,随着水深的加大各重金属溶解态含量趋于平衡,说明水动力作用时悬浮颗粒越集中,对水体溶解态重金属含量吸附越大,不同流速、不同水深处 Cu、Zn、Pb 重金属含量(y,μg/L)与距沉积物的距离(x,cm)关系为:

流速为 45 cm/s 时

$$y = C_0 + 3.142\ln x \quad (R^2 = 0.935) \tag{1}$$

$$y = C_0 + 4.562\ln x \quad (R^2 = 0.927) \tag{2}$$

$$y = C_0 + 9.188\ln x \quad (R^2 = 0.982) \tag{3}$$

流速为 65 cm/s 时

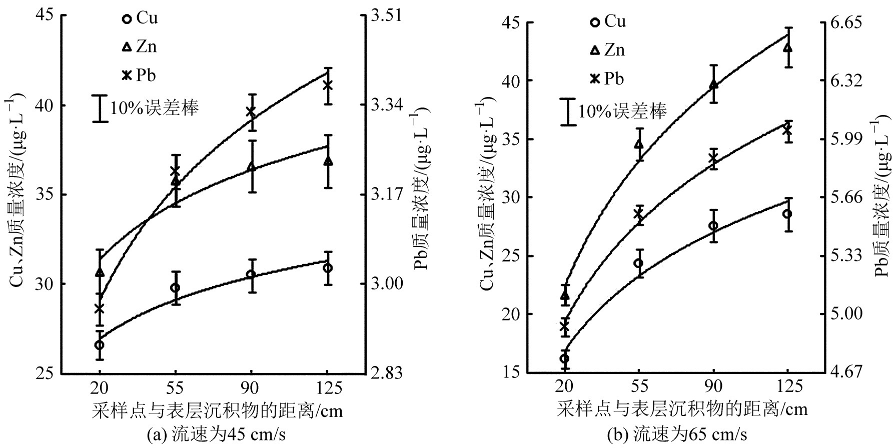

图 3　不同水深处各重金属溶解态含量和水体与沉积物距离的关系曲线

Fig. 3　Relationship curves between content of dissolved heavy metals of different water depths and distance to sediment

$$y = C_0 + 9.199\ln x \quad (R^2 = 0.966) \tag{4}$$

$$y = C_0 + 15.442\ln x \quad (R^2 = 0.986) \tag{5}$$

$$y = C_0 + 24.568\ln x \quad (R^2 = 0.992) \tag{6}$$

式中　C_0——水体距沉积物 20 cm 处各溶解态重金属含量，μg/L

3　试验结果在鄱阳湖中的应用

2.3 节建立了不同流速下不同水深处溶解态重金属含量 y 和水体与沉积物的距离 x 的关系，将此关系式应用于鄱阳湖野外实测试验中，以检验所建关系式的适用性。

2013 年 4 月 23—25 日在鄱阳湖大桥断面和星子段进行了野外试验（鄱阳湖大桥断面及星子段沉积物颗粒分布曲线见图 4，监测断面沉积物初始值见表 2），试验时在采水器下悬挂 10 kg 的铅球，确保采水器放入水中能保持竖直，试验时经历了中风和大风，具有较好的代表性，采样时 2 断面流速分别为 39、75 cm/s 和 44、68 cm/s，同一流速时同时采集与沉积物距离分别为 0.3、0.8、1.3、1.8 m 共 4 种水深处水样，分别测定溶解态重金属含量，为减少误差，每一水深处平行采样 3 次后求平均值，将流速为 39、44 cm/s 时的测定值分别代入式（1）～（3）中，流速为 75、68 cm/s 时测定值分别代入式（4）～（6）中，将实测值与计算值进行对比，结果表明两者相对误差均在 ±15% 范围内，计算值与实测值结果比较见表 3，结果表明式（4）～（6）在水体流速为 65～75 cm/s 的情况下均适用，同时也说明所建立的关系式基本合理。

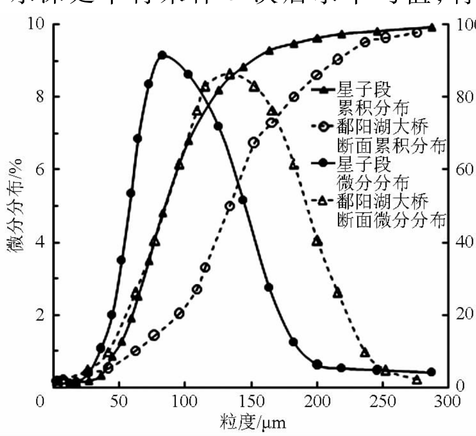

图 4　沉积物粒度分布曲线

Fig. 4　Distribution curves of sediment particle size

表 2　监测断面沉积物基本特性参数

Tab. 2　Basic parameters of sediment at Xingzi section and Poyang Lake bridge section

项目	重金属质量比/(mg·kg⁻¹)				含水率/%
	Cu	Zn	Cd	Pb	
星子段	43.16～71.54	63.57～98.12	4.23～17.46	41.53～85.51	96.0±0.4
鄱阳湖大桥断面	41.23	78.17	4.90	36.38	95.7±0.5

4　结论

（1）水动力作用时会造成沉积物的再悬浮，继而沉积物中有部分重金属会释放到水体中，Cu、Zn、Pb 主要以溶解态释放，Cd 主要以悬浮态释放，悬浮的沉积物会吸附水体中溶解态的重金属，吸附量与悬浮的沉积物量有关。

（2）中水动力和强水动力下，水体中溶解态 Cu、Zn、Pb 含量从底层水体至表层水体呈对数增长。

（3）鄱阳湖野外试验表明，本文建立的关系式基本合理，计算值与实测值的相对误差在 ±15% 范围内，说明本试验装置基本合理，操作性较好。

（4）由于本研究中室内及室外试验沉积物均为鄱阳湖沉积物，说明所建立的关系式对应沉积物粒径在 50～200 μm 范围内适用，而对其他粒径的沉积物下水体中溶解态重金属含量是否满足此关系式有待进一步研究。

表3 不同流速、不同水深处各重金属溶解态含量计算值与实测值的比较

Tab. 3 Comparison of calculation results and measured values under different hydrodynamic conditions and water depths

流速/(cm·s⁻¹)	参数	水深/m											
		0.3			0.8			1.3			1.8		
		Cu	Zn	Pb	Cu	Zn	Pb	Cu	Zn	Pb	Cu	Zn	Pb
39	计算值/(μg·L⁻¹)	18.7	24.4	2.7	25.9	31.8	3.9	27.4	35.7	4.3	28.6	36.9	4.4
	实测值/(μg·L⁻¹)	17.3	21.5	2.3	28.4	29.3	3.6	29.6	38.6	4.8	26.1	39.5	4.8
	相对误差/%	-7.49	-11.89	-14.81	9.65	-7.86	-7.69	8.03	8.12	11.63	-8.74	7.05	9.09
75	计算值/(μg·L⁻¹)	23.5	31.7	3.1	32.1	39.2	4.7	35.7	43.5	5.2	36.8	44.6	5.4
	实测值/(μg·L⁻¹)	21.1	28.2	3.5	35.9	36.4	4.9	31.4	47.8	4.8	39.2	48.5	5.1
	相对误差/%	-10.21	-11.04	12.90	11.84	-7.14	4.26	-12.04	9.89	-7.69	6.52	8.74	-5.56
44	计算值/(μg·L⁻¹)	21.6	26.5	4.3	27.2	32.7	5.7	29.4	35.2	6.1	30.1	37.1	6.3
	实测值/(μg·L⁻¹)	19.6	28.9	4.1	28.7	35.6	6.2	31.9	38.4	5.7	33.4	38.6	6.8
	相对误差/%	-10.20	8.30	-4.88	5.23	8.15	8.06	7.84	8.33	-7.02	9.88	3.89	7.35
68	计算值/(μg·L⁻¹)	27.2	33.6	5.9	35.6	39.8	7.3	37.4	44.1	7.8	38.1	46.2	8.0
	实测值/(μg·L⁻¹)	28.7	30.2	6.3	33.1	43.5	7.2	34.3	43.8	8.3	36.2	44.7	8.5
	相对误差/%	5.51	-10.12	6.78	-7.02	9.30	-1.37	-8.29	-0.68	6.41	-4.99	-3.25	6.25

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