A Review of Proposed Techniques for Modeling Longitudinal Dispersion Coefficient in Natural Channels

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Abstract-**The World is facing a global climate change, while the world's population continues to grow. Therefore, providing sufficient water has become increasingly difficult in the last few decades. Artificially providing fresh water requires complex technology and economic investment. This is almost impossible, especially in underdeveloped countries. Due to these issues, water scarcity and/or stress is expected to rise dramatically in many regions in the world in the near future. Furthermore, current fresh water resources are vulnerable to pollutants (nuclear, biological, physical, and chemical). Conservation of fresh water resources has therefore become a critical issue. As is well known, the main fresh water sources are rivers and natural streams. Convective longitudinal dispersion is the most effective parameter in such sources. The longitudinal dispersion coefficient represents the rate of pollution and it is mostly used in water pollution modeling studies. Hence, learning the longitudinal dispersion mechanism in natural channels is vitally important to control water pollution. This paper's main purpose is to present a significant review and criticism on the literature related to both the longitudinal dispersion mechanism and the modeling techniques proposed for determining longitudinal dispersion coefficient in natural channels.**

Keywords- Dispersion; Dimensional and Dimensionless Longitudinal Dispersion Coefficient; Natural channels; Water Pollution Control

I. INTRODUCTION

We are experiencing a significant rise in the world's population. Toprak et al. (2012) and Toprak et al. (2013a) indicate that according to revised UN estimations (UN, 2006), the world population is likely to increase by 2.5 billion over the next 43 years, growing from the current 6.7 billion to 9.2 billion in 2050. This increase value is equivalent to the total size of global population in 1950, and it will be experienced mostly by underdeveloped regions, whose population is projected to rise from 5.4 billion in 2007 to 7.9 billion in 2050 [1-2]. However, freshwater resources do not grow at the same rate; they remain constant. Water sources will therefore become smaller per capita every year. On the other hand, global climate change (GCC), which also affects water resources, is another serious problem. Many published studies report evidence of the existence of GCC. Herein, the literature related to GCC is not reviewed and presented in detail; however, it will be useful to mention Toprak et al. (2013b). This paper indicates that although there is no general consensus among scientists on the dimensions, causes, and effects of GCC, it is possible to confirm that human beings are currently experiencing it and that the atmosphere is warming up [3]. Due also to technological developments and the increase in human welfare, a significant increase in both diversity of water consumption and per capita water use is expected. Paralleling the technological developments in the irrigated agricultural sector, it seems possible to provide a greater variety and quantity of food; however, water resources are limited. Therefore, water stress and/or scarcity is expected to rise dramatically in numerous regions around the world in the near future. Another problem humans are currently facing is water trade. Water sellers deprive people of their water resources. Consequently, people are forced to buy their water from someone else. Currently, the water trade and the International Water Forum are protested and opposed globally.

Since water stress/scarcity has potentially serious effects on almost all life sectors, "sustainably supplying clear fresh water" is becoming the key issue discussed among scientists, particularly among local administrators in addition to politicians and people in different aspects of life in the last few decades [1-2]. The greatest problem that needs to be urgently solved is controlling water pollution in both irrigation and domestic water-distribution-networks, as well as in natural channels. Water quality control techniques in natural channels are dependent on the mechanism of longitudinal dispersion (LD). Learning the LD is therefore critical to be able to control all kinds of pollution (i.e., physical, chemical, biological, and nuclear) in natural channels. In order to be able to reduce pollution, it first has to be correctly determined or estimated. In various published studies, numerous approaches have been suggested to achieve this goal. However, some of these depend on methods calibrated only with data (i.e. genetic algorithms, artificial neural networks, and many other black-box methods). These cannot be generalized unless they are redesigned against different data sets. Furthermore, Toprak et al. (2012a) and Toprak et al. (2013) suggest that since such models or algorithms have high computational demands, the requirement of expensive technical computing software is still unavoidable. In order to be confidently used for this purpose, the methods should be scientifically generalizable, logically acceptable, mathematically accurate, technically applicable, and easily usable [1-2].

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In this study, we first present the mechanism of the LD briefly. We then clarify the issue's importance. After providing the LD's background, we classify numerous, highly valuable, published works that are up-to-date on the issue. These works are then briefly reviewed, criticized, and discussed. We also provide a brief explanation of our comparison criteria. (This is crucial in order to be able to check any model's reliability against the reliable measured/observed data.) Finally, we offer our conclusions.

II. THE PHYSICAL MECHANISM OF THE LONGITUDINAL DISPERSION

The longitudinal dispersion coefficient (LDC; D_1, in m^2/s) represents the rate of pollution in open canal flows. Therefore, LDC is the most significant variable in any water pollution modeling study. Toprak (2004) states that in any open canal flow, a pollutant's entry and dispersion within the water requires three different physical mechanisms. These are: 1) molecular diffusion, 2) advection dispersion, (i.e., longitudinal transport due to the velocity of the medium), and 3) the dispersion depends only on turbulence. Although dispersion occurs in three dimensions, two- or one-dimensional dispersion is only required for modeling in many cases. Due to convective dispersion, a one-dimensional equation of motion is significant and the longitudinal dispersion coefficient, D_1, must be obtained prior to modeling. For obtaining D_1 there are various procedures available in the current literature [4]. As can be easily understood from Toprak (2004), Toprak and Savci (2004), Toprak et al. (2004a), Toprak et al. (2004b), Toprak et al. (2004c), Toprak and Savcı (2007), Toprak and Cigizoglu (2008), Toprak et al. (2012b), and Toprak et al. (2014), the experimental and theoretical studies on longitudinal dispersion coefficient were initiated by Taylor (1953) and Taylor (1954) and are now continued by many other researchers who have tried to explain the longitudinal dispersion mechanism in prismatic and natural channels [4-14].

According to Jobson (1997), Kilpatrick (1993) modified the lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a centered single slug injection of tracer (Fig. 1) [15]. The modification done by Kilpatrick (1993) is acceptable as a good representation for the travel time of a tracer injected into single points in long channels.

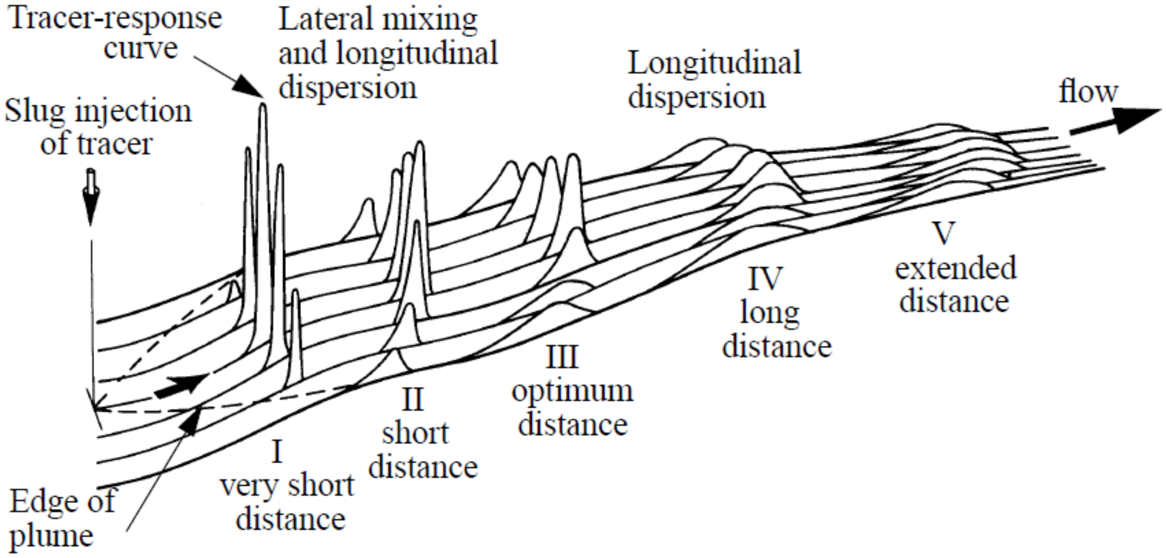

Fig. 1 Lateral mixing and longitudinal dispersion patterns and changes in distribution of concentration downstream from a single center slug injection of a tracer modified from Kilpatrick, 1993, p.2. [15]

III. THE ISSUE'S IMPORTANCE

As Jobson (1997) says, the possibility of a contaminant (nuclear, biological, chemical, and/or physical) being accidentally or intentionally spilled upstream into a natural channel is a constant concern for those who use water downstream from the area of the spill. Such situations occur in irrigated areas, industrial districts, and war zones [15]. The author explains why the subject is crucial to estimate in the following categories: 1) the rate of movement of a contaminant through a river reach, 2) the rate of attenuation of the peak concentration of a conservative contaminant with time, and 3) the length of time required for the contaminant plume to pass a point in the river for practical and theoretical reasons [15].

Although many excellent approaches exist to estimate travel time and dispersion in the current literature, Jobson (1997) indicates that none can be used with confidence before calibration and verification to the particular river reach in question. Therefore, in order to estimate the rate of movement, dilution, and mixing of contaminants in rivers or streams, reliable models, authentic studies, experiments that simulate real conditions, and carefully recorded and reported data are still needed [15].

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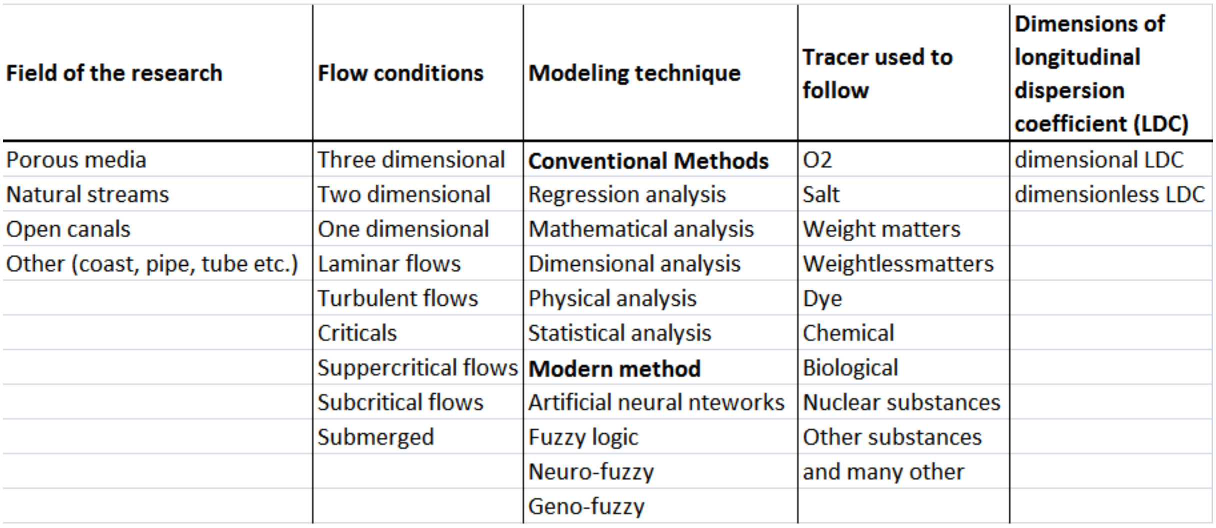
IV. BACKGROUND OF THE LITERATURE OF LDC

We can point out that the experimental and theoretical studies were initiated by Taylor (1953) and Taylor (1954) [13-14], and were then somewhat expanded by Scheidegger (1954), Elder (1959), Parker (1961), Fischer (1967), Thackston and Krenkel (1967), Fischer (1968a), Fischer (1968b), Sayre (1968), Sayre and Chang (1968), Fischer (1969), and Sooky (1969) [16-26]. However, since technology was not yet well-developed at that time of these studies, they do not offer highly accurate measurements. Nonetheless, they may still be considered a basis for the understanding of the physical mechanism of dispersion. Fischer's study, in particular, was a major contribution in moving the studies from their infancy into a more developed stage, which includes studies by Yotsukura et al. (1970), Atesman (1970), Godfrey and Frederick (1970), Bansal (1970), Sümer (1970), Bansal (1971), Chang (1971), Savci (1972), Fukooka and Sayre (1973), Savcı (1973), McQuivey and Keefer (1974), Nordin and Sabol (1974), Day (1975), Fischer (1975), Abd El-Hadi and Davar (1976), Liu (1977), and Fischer et al. (1979) [26-43]. These studies provided a valuable foundation for the next group of researchers: Chatwin (1980), Graf (1986), Yu and Wenzhi (1989), Guymer and West (1992), Zhang (1995), Al Naib and Sanders (1997), Basha (1997), Bogle (1997), Jackel and Vereecken (1997) [44-52], Jobson (1997) [15], Strack and Fairbrother (1997), Guymer (1998), Koussis and Rodriguez-Mirasol (1998), Seo and Cheong (1998), Benson et al. (2000), Huang and Yu (2000), and Swamee et al. (2000) [53-59]. This period (1980 – 2000) can be accepted as the middle age of the investigations. Technology by this time was more developed and the measurements are therefore more precise. By this point, computer assistance was just beginning to emerge. Relevant studies published in the period 2001 - present are listed as Baeumer et al. (2001), Deng et al. (2001), Gandolfi et al. (2001), Pasquero et al. (2001), Deng et al. (2002), Ho et al. (2002), Kashefipour and Falconer (2002), Seo and Baek (2004) [60-67], Toprak (2004), Toprak and Savci (2004), Toprak et al. (2004a), Toprak et al. (2004b), Toprak et al. (2004c) [4-8], Makinia and Wells (2005), Rowinski et al. (2005), Smith et al. (2006). Tayfur (2006) [68-71], Toprak and Savci (2007) [9], Baek and Seo (2008), Jha and Singh (2008), Rowinski et al. (2008) [72-74], Toprak and Cigizoglu (2008) [10], Hossien, et al. (2009), Noori et al. (2009), Riahi-Madvar et al., (2009), Yearsley (2009), Adarsh (2010), De Melo Ribeiro et al. (2010), Shen et al. (2010), Shieh, et al. (2010), Liu et al. (2011), Noory et al. (2011), Ranjan (2011), Xiaodong et al. (2011), Zhang (2011), Taormina et al. (2012), Zhang et al. (2012) [75-89], and Toprak et al. (2014) [12]. These studies are more confident, the measurements and/or data are more accurate, and there is a significant development in computer technology. Recently, many black box modeling techniques that depend only on data (i.e. ANN, GA, etc.) can be found in the literature. These are usually referred to as artificial intelligence methods. The models that employ these methods, however, have no physical basis. Thus, mathematical, physical, and/or statistical models are still needed. The next stage of research (the mature or adult stage) employs less black-box method and relies more on physical models.

V. CLASSIFICATION OF THE PREVIOUS WORKS

The quality of the research studies on this topic depends mostly on technological developments at the time of writing. More recent studies are more accurate, more complex, and they offer great opportunities for further research. Numerous scientific studies on the topic have been already published, and the number of such papers dramatically increases every year. It is therefore impossible to evaluate all of them individually in this paper. Instead, we classify such studies according to specific criteria. This means that some are mentioned only briefly while others are discussed in depth. Although it is possible to classify the studies under many different categories, we have deemed five main classes as appropriate and necessary. Our classification is made according to: 1) the field of the research, 2) the flow conditions, 3) the modeling technique, 4) the tracer used, and 5) dimensions of longitudinal dispersion coefficient (LDC) (as given with their subclasses in Table 1).

TABLE 1 CLASSIFICATION OF THE STUDIES PERFORMED ON LONGITUDINAL DISPERSION COEFFICIENT



Field of the research	**Flow conditions**	**Modeling technique**	**Tracer used to follow**	**Dimensions of longitudinal dispersion coefficient (LDC)**
Porous media	Three dimensional	**Conventional Methods**	O2	dimensional LDC
Natural streams	Two dimensional	Regression analysis	Salt	dimensionless LDC
Open canals	One dimensional	Mathematical analysis	Weight matters	
Other (coast, pipe, tube etc.)	Laminar flows	Dimensional analysis	Weightlessmatters	
	Turbulent flows	Physical analysis	Dye	
	Criticals	Statistical analysis	Chemical	
	Suppercritical flows	**Modern method**	Biological	
	Subcritical flows	Artificial neural nteworks	Nuclear substances	
	Submerged	Fuzzy logic	Other substances	
		Neuro-fuzzy	and many other	
		Geno-fuzzy		

VI. CLASSIFICATION ACCORDING TO THE PURPOSE OF RESEARCH

The works that propose any model or method can be ordered chronologically as Taylor (1953) ,Taylor (1954) [13-14], Fischer (1968a), Fischer (1968b) [21-22], McQuivey and Keefer (1974) [37], Liu (1977) [42], Basha (1997) [50], Koussis and Rodriguez-Mirasol (1998), Seo II and Cheong (1998) [55-56], Ho et al. (2002), Kashefipour and Falconer (2002), Seo II and Baek (2004) [66-67], Toprak (2004), Toprak and Savci (2004) [4-5], Tayfur (2006) [71], Toprak and Savcı (2007) [5], Baek and Seo (2008) [72], Toprak and Cigizoglu (2008) [10], Hossien et al.(2009), Noori et al. (2009), Riahi-Madvar et al. (2009) [75-77], Adarsh (2010), De Melo Ribeiro et al. (2010), Shen et al. (2010), Shieh et al. (2010) [79-82], Noori et al. (2011), Ranjan (2011), and Zhang (2011) [84-87].

The works that report measurements, observations, or data sets can be presented chronologically as Taylor (1953), Taylor (1954) [13-14], Sayre and Chang (1968) [24], Goodfrey and Frederick (1970) [29], Yotsukura et al. (1970) [27], Chang (1971) [33], Fukooka and Sayre (1973)[35], McQuivey and Keefer (1974), Nordin and Sabol (1974), Day (1975) [37-39], Chatwin (1980), Graf (1986) [44-45], Guymer and West (1992), Zhang (1995) [47-48], Jobson (1997) [15], Guymer (1998) [54], Deng, et al. (2001) [61], Deng, et al. (2002) [64], Jha and Singh (2008), Rowinski et al. (2008) [73-74], Shen et al. (2010) [81], Liu et al. (2011) [83], and Xiaodong et al. (2011) [86].

The published studies that present reviews on works on longitudinal dispersion can be ordered chronologically as Sooky (1969) [26], Sümer (1970) [31], Fischer (1975) [40], Fischer et al. (1979) [43], Swamee et al. (2000) [59], Gandolfi et al. (2001) [62], Toprak (2004) [4], Toprak et al. (2004a), Toprak et al. (2004b) [6-7], Makinia and Wells (2005), Rowinski et al. (2005) [68-69], De Melo Ribeiro et al. (2010) [80], and Noori et al. (2011) [84].

The studies that report physical, mathematical, and/or dimensional analyses can be listed chronologically as Taylor (1953) [13], Scheidegger (1954) [16], Taylor (1954) [14], Elder (1959) [17], Parker (1961) [18], Fischer (1967), Thackston and Krenkel (1967) [19-20], Sayre (1968) [23], Fischer (1969), Sooky (1969) [25-26], Atesman (1970) [28], Bansal (1970), Sümer (1970) [30-31], Savci (1972) [34], Savci (1973) [36], Abd El-Hadi and Davar (1976) [41], Fischer (1979) [43], Yu and Wenzhi (1989) [46], Zhang (1995) [48], Al Naib, S. and Sanders, J. (1997) [49], Bogle (1997), Jackel and Vereecken (1997), Strack and Fairbrother (1997) [51-53], Bensonet al. (2000), Huang and Yu (2000) [57-58], Baeumeret al (2001) [60], Pasquero et al. (2001) [63], Toprak (2004) [5], Smith et al (2006) [70], Yearsley (2009) [78], De Melo Ribeiro et al. (2010) [80], Xiaodong et al. (2011), and Zhang (2011) [86-87].

VII. CLASSIFICATION ACCORDING TO RESEARCH FIELD

The works performed on real media can be classified into four categories:

1) Porous media (Scheidegger, 1954; Smith et al., 2006) [16, 70].

2) Natural streams (channels, rivers, etc.): There many current studies in this category. Some of these are, listed chronologically: Fischer (1967), Thackston and Krenkel (1967) [19-20], Fischer (1968a), Fischer (1968b) [21-22], Fischer (1969) [25], Bansal (1970), Goodfrey and Frederick (1970) [29-30], Yotsukura et al., (1970) [27], Bansal (1971), Chang (1971) [32-33], McQuivey and Keefer (1974), Nordin and Sabol (1974) [37-38], Day (1975), Fischer (1975) [39-40], Liu (1977) [42], Graf (1986) [45], Yu and Wenzhi (1989) [46], Al Naib and Sanders (1997) [49], Jobson (1997) [15], Koussis and Rodriguez-Mirasol (1998), Seo II and Cheong (1998) [55-56], Strack and Fairbrother (1997) [53], Huang and Yu (2000), Swameeet al. (2000) [58-59], Deng et al. (2001), Gandolfiet al. (2001) [61-62], Deng et al. (2002), Ho et al. (2002), Kashefipour and Falconer (2002) [64-66], Toprak (2004), Toprak and Savci (2004), Toprak et al. (2004a), Toprak et al. (2004b) [4-7], Tayfur (2006) [71], Seo II and Baek (2004) [67], Rowinskiet al. (2005) [69], Toprak and Savcı (2007) [9], Jha, and Singh (2008) [73], Toprak and Cigizoglu (2008) [10], Rowinski et al. (2008) [74], Hossien et al. (2009), Riahi-Madvar, et al. (2009), Yearsley (2009), Adarsh (2010), De Melo Ribeiroet al. (2010), Shenet al. (2010) [75-81], Noori,et al. (2011), and Ranjan, (2011) [84-85].

3) Canals (artificial/prismatic canal): In this category, we can mention Sayre (1968), Sayre and Chang (1968) [23-24], Sooky (1969) [26], Atesman (1970) [28], Fukooka and Sayre (1973) [35], Basha (1997) [50], Guymer (1998) [54], and Baek and Seo II (2008) [72].

4) Other (coast, pipe, tube etc.): Taylor (1953), Taylor (1954) [13-14], Parker (1961) [18], Fischer et al. (1979) [43], Guymer and West (1992) [47], and Smith et al. (2006) [70] are noteworthy in this category.

VIII. CLASSIFICATION ACCORDING TO FLOW CONDITIONS

We sub-classified the studies in this class into nine categories: three-dimensional flows, two-dimensional flows (Baek and Seo, 2008); Pasquero et al., 2001; Zhang, 2011 [72, 63, 87]), one-dimensional flow (all the studies made on longitudinal dispersion can be mentioned in this category), laminar flows, turbulent flows (Atesman, 1970; Elder, 1959; Pasquero et al., 2001 [28, 17, 63]), critical flows, supercritical flows, subcritical flows, and submerged flows (Al Naib and Sanders, 1997; Savci, 1972; Savci, 1973 [49, 34, 36]).

IX. CLASSIFICATION ACCORDING TO MODELING TECHNIQUE

The studies in this class can be sub-classified mainly into two categories:

1) Conventional techniques (regression analysis, mathematical analysis, dimensional analysis, physical analysis, and statistical analysis): Works that propose any model or method can be chronologically ordered as Taylor (1953) [13], Scheidegger (1954) [16], Taylor (1954) [14], Elder (1959) [17], Parker (1961) [18], Fischer (1967), Thackston and Krenkel (1967), Fischer (1968a), Fischer (1968b), Sayre (1968), Sayre and Chang (1969) [19-24], Sooky (1969) [26], Atesman (1970) [28], Bansal (1970), Sümer (1970) [30-31], Goodfrey and Frederick (1970) [29], Yotsukura et al. (1970) [27], Chang (1971), Savci (1972), Fukooka and Sayre (1973), Savci (1973), McQuivey and Keefer (1974), Nordin and Sabol (1974), Day (1975), Fischer (1975), Abd El-Hadi and Davar (1976), Liu (1977), Fischer et al. (1979), Chatwin (1980) [33-44], Graf (1986) [45], Yu and Wenzhi (1989) [46], Guymer and West (1992) [47], Zhang (1995) [48], Al Naib and Sanders (1997), Basha (1997), Bogle (1997), Jackel and Vereecken (1997) [49-52], Jobson (1997) [15], Strack and Fairbrother (1997), Guymer (1998), Koussis and Rodriguez-Mirasol (1998), Seo II and Cheong (1998), Bensonet al. (2000), Huang and Yu (2000), Swamee et al. (2000), Baeumeret al (2001), Deng, et al. (2001), Gandolfi et al. (2001), Pasquero et al. (2001) [53-63], Ho et al. (2002), Kashefipour and Falconer (2002), Seo II and Baek (2004), Makinia and Wells (2005) [65-68], Smith et al (2006) [70], Baek and Seo (2008), Jha and Singh (2008), Rowinski et al. (2008) [72-74], Yearsley (2009) [78], De Melo Ribeiro et al. (2010), Shen et al. (2010) [80-81], Liu et al. (2011) [83], Xiaodong et al. (2011), and Zhang (2011) [86-87].

2) Modern techniques (i.e. soft computing techniques, artificial neural networks, fuzzy logic, neuro-fuzzy, geno-fuzzy, ANFIS, etc.): In this category, we can mention Toprak (2004) [4], Toprak et al. (2004a), Toprak et al. (2004b) [6-7], Toprak and Savci (2004) [5], Rowinski et al. (2005) [69], Tayfur (2006) [71], Toprak and Savcı (2007), Toprak and Cigizoglu (2008) [9-10], Hossien et al. (2009), Noori et al. (2009), Riahi-Madvar et al. (2009) [75-77], Adarsh (2010) [79], Shieh et al. (2010) [82], Noori et al., (2011), Ranjan (2011) [84-85], Zhang et al. (2012) [89].

X. CLASSIFICATION ACCORDING TO TRACER USED TO FOLLOW

O2, salt, weight matters, weightless matters, dye, chemical substances, biological substances, nuclear substances, and other substances.

XI. CLASSIFICATION ACCORDING TO DIMENSION OF LONGITUDINAL DISPERSION COEFFICIENT

The studies in this class can be classified into two main categories:

1) Studies performed for modeling dimensional LDC: Almost all published works report or propose models to determine dimensional LDC. These include Taylor (1953) [13], Scheidegger (1954) [16], Taylor (1954) [14], Parker (1961) [18], Fischer (1967), Thackston and Krenkel (1967), Fischer (1968a), Fischer (1968b), Sayre (1968), Sayre and Chang (1968), Fischer (1969), Sooky (1969) [19-26], Atesman (1970) [28], Bansal (1970), Sümer (1970) [30-31], Goodfrey and Frederick (1970) [29], Yotsukura et al. (1970) [27], Chang (1971), Savci (1972), Fukooka and Sayre (1973), Savci (1973), McQuivey and Keefer (1974), Nordin and Sabol (1974), Day (1975), Fischer (1975), Abd El-Hadi and Davar (1976), Liu (1977), Fischer (1979), Chatwin (1980), Graf (1986), Yu and Wenzhi (1989), Guymer and West (1992), Zhang (1995), Al Naib and Sanders (1997), Basha (1997), Bogle (1997), Jackel and Vereecken (1997) [33-52], Jobson (1997) [15], Strack and Fairbrother (1997), Guymer (1998), Koussis and Rodriguez-Mirasol (1998) [53-55], Bensonet al. (2000), Huang and Yu (2000), Swamee et al. (2000), Baeumeret al (2001), Deng, et al. (2001), Gandolfi et al. (2001), Pasquero et al. (2001) [57-63], Ho et al. (2002), Kashefipour and Falconer (2002), Seo II and Baek (2004) [65-67], Toprak (2004) [4], Toprak et al. (2004a), Toprak et al. (2004b) [6-7], Makinia and Wells (2005), Rowinski et al. (2005), Smith et al (2006), Tayfur (2006) [68-71], Toprak and Savcı (2007) [9], Baek and Seo (2008), Jha and Singh (2008), Rowinski et al. (2008) [72-74], Toprak and Cigizoglu (2008) [10], Hossien et al. (2009), Noori et al. (2009), Riahi-Madvar et al. (2009), Yearsley (2009), Adarsh (2010), De Melo Ribeiro et al. (2010), Shen et al. (2010), Shieh et al. (2010), Liu et al. (2011), Noori et al., (2011), Ranjan (2011), Xiaodong et al. (2011), Zhang (2011), and Zhang et al. (2012) [75-89].

2) Studies performed for modeling dimensionless LDC: Only a few published works propose models or empirical equations to determine dimensionless LDC. These are Elder (1959) [17], Fischer et al. (1979) [43], Seo II and Cheong (1998) [56], Toprak (2004), Toprak and Savci (2004) [4-5], and Toprak et al. (2014) [12].

XII. FOCUSING ON THE ASSUMPTIONS MADE IN MODELING LDC

There are many related studies available in the current literature. Most of these studies have the following aims: 1) to investigate the mechanism of the dimensional LD in natural channels, and 2) to model dimensional LDC. Although there is a large number of published studies that propose models to predict dimensional LDC, there are only a few published works that propose models to estimate dimensionless LDC. However, the equations using dimensionless LDC (D_1') have more generality than the dimensional ones [12]. In almost all modeling techniques the media has been assumed as one-dimensional. This assumption is acceptable for LDC in natural streams. Another two important assumptions are homogeneity and isotropy, which are made for simpler solutions, as was the case with the one-dimensional (1D) dispersion equation of Taylor (1954) [14].

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Depth uniformity is another assumption that these studies make. The dispersion of any pollutant within the water media depends physically not only on advection dispersion, but also on molecular diffusion and turbulence dispersion. However, the advection dispersion can be accepted in many cases as the most important dispersion mechanism, especially in natural streams. Thus, molecular diffusion and turbulence dispersion are often neglected.

XIII. A BRIEF DISCUSSION ON STUDIES USING THE SAME VARIABLES

Consideration of all the points mentioned above leads to the one-dimensional (1D) dispersion equation (Equation 1) derived by Taylor (1954) [14]:

$$A\left(\frac{\partial C}{\partial t}\right) = -UA\left(\frac{\partial C}{\partial x}\right) + \left(\frac{\partial}{\partial x}\right)\left[D_1 A\left(\frac{\partial C}{\partial x}\right)\right] \quad (1)$$

where C , x, A, U, and D_1 are the pollutant concentration, the distance along the channel direction, the cross-sectional area, the cross-sectional average velocity, and the dispersion coefficient, respectively. As previously established, homogeneity and isotropy of the media are two assumptions made in the derivation of this expression. Furthermore, the channel is assumed to have uniform depth, the lateral dispersions and molecular diffusions are negligible, and the flow is assumed to be permanent. This means that the LDC does not change with time or space. Therefore, the analysis provided by Taylor (1954) [14] can be applied only after an adequate mixing of the reach of the natural channel. In other words, Equation (1) is not valid at the initial times and around the entry place of the pollutant into the channel. Toprak and Savci (2007), Toprak and Cigizoglu (2008) [9-10], and Toprak et al. (2014) [12] indicate that for validation of Equation (1), there must be a sufficient time duration and distance from the source so that the pollutant is uniformly mixed with the water.

Elder (1959) [17], Fischer (1975) [40], Liu (1977) [42], Seo and Cheong (1998) [56], Koussis and Rodriguez-Mirasol (1998) [55], Kashefipour and Falconer (2002) [66], Toprak (2004) [4], Toprak and Savci (2007), Toprak and Cigizoglu (2008) [9-10], and Toprak et al. (2014) [12] use the same variables for modeling. So do the works that are reviewed in detail here. The equations were given in both dimensional and dimensionless forms. The equations in dimensionless form are followed by the authors' original formulations, which are mostly in dimensional form.

Elder (1959) [17] reports the results of experiments performed to achieve the longitudinal dispersion coefficient by assuming a logarithmic vertical-velocity distribution to give the Eq. (2):

$$D_1 = 5{,}93HU_* \Rightarrow D_1^{'} = \frac{D_1}{HU_*} = 5{,}93 \quad (2)$$

Where, $D_1^{'}$ is the dimensionless longitudinal dispersion coefficient, which equal to $\frac{D_1}{HU_*}$, U_* is the bed shear-stress velocity, and H the depth of the flow. However, Toprak (2004) [4] says Equation (2) does not accurately describe dimensionless LDC in natural streams. The author found that the results significantly underestimate the observed coefficients. Although Toprak indicates that this is thought to be mainly due to the exclusion of the transverse variation in the velocity profile across the stream in the derivation of Elder's equation, it should be noted that Elder (1959) [17] might perform his experiment on the pipe flows.

Fischer (1975) [40] developed a clearer equation to predict the LDC, which is a simplified non-integral form of Fischer (1967) [19] and given as:

$$D_1 = 0{,}011U^2 W^2 HU_* \Rightarrow D_1^{'} = \frac{D_1}{HU_*} = 0{,}011U^2 W^2 \quad (3)$$

Where W is the width of the channel.

By using Fischer (1967) [19]'s equation, Liu (1977) [42] derived another equation to determine LDC taking into account the role of lateral velocity gradients in dispersion in natural streams. This is given as:

$$D_1 = \beta U^2 W^2 H U_* \Rightarrow D_1^{'} = \frac{D_1}{H U_*} = \beta U^2 W^2 \quad \beta = 0{,}18\left(\frac{U_*}{U}\right)^{1.5} \quad (4)$$

Seo and Cheong (1998) [56] used dimensional and regression analyses to derive an equation using the one-step Huber method through 59 data sets, measured in 26 rivers in the USA. The authors used 35 of the measured data sets to establish their equation; the other data sets were used for verification (Equation 5).

$$\frac{D_1}{HU_*} = 5.915\left(\frac{W}{H}\right)^{0.62}\left(\frac{U}{U_*}\right)^{1.428} \tag{5}$$

By using the original theory and equation proposed by Fischer (1967) [19], Fischer (1968a), Fischer (1968b) [21, 22], and Fischer (1969) [25], and also applying the von Karman defect law, Koussis and Rodriguez-Mirasol (1998) [55] derived Equation (6):

$$D_1 = \frac{\phi\, U^* \, W^2}{H} \Rightarrow D_1^{'} = \frac{D_1}{HU_*} = \frac{\phi\, W^2}{H^2} \tag{6}$$

By applying a regression analysis on 16 field data sets, the authors obtained the value of ϕ as 0.6.

Kashefipour and Falconer (2002) [66] developed two equations (Eqs. 7 and 8) by using regression analyses to predict the LDC in riverine flows. The derivation is based on 81 of the measured data sets obtained from 30 rivers at different times in the USA. This study is one of the recent studies done to estimate LDC in natural channels (an estimation that relies on measured data).

$$D_1 = 10.612\, H\, U\, \frac{U}{U^*} \Rightarrow D_1^{'} = \frac{D_1}{HU_*} = 10.612\,\frac{U^2}{U_*^2} \tag{7}$$

$$\begin{aligned} D_1 &= \left[7{,}428 + 1{,}775\left(\frac{W}{H}\right)^{0.62}\left(\frac{U_*}{U}\right)^{0.572}\right] H\left(\frac{U^2}{U_*}\right) \\ D_1^{'} &= \frac{D_1}{HU_*} = \left[7{,}428 + 1{,}775\left(\frac{W}{H}\right)^{0.62}\left(\frac{U^*}{U}\right)^{0.572}\right]\left(\frac{U^2}{U_*^2}\right) \end{aligned} \tag{8}$$

The authors pointed out that the hydraulic and geometric parameters of the flow were taken under consideration when deriving the equations. However, other researchers have not approved these equations. This work is discussed in detail in Toprak et al. (2004a) [6], Toprak (2004) [4], and Toprak and Savci (2007), Toprak and Cigizoglu (2008) [9-10].

A fuzzy-logic-based model to predict LDC for natural channels by using the same variables was introduced first by Toprak (2004) [4]. The author compared his model to the models proposed by the above-mentioned researchers. Later, Toprak and Savci (2007) [9] discussed and approved the results of Toprak (2004) [4].

Toprak and Cigizoglu (2008) [10] proposed an ANN-based model for the same goal and compared their results to the results of the fuzzy-logic-based model proposed by Toprak (2004) [4] and Toprak and Savci (2007) [9], as well as to the results of the models proposed in previous studies.

Toprak et al. (2014) proposed two models to estimate the dimensionless LDC. The models are based on fuzzy logic and ANN [12]. The results of these two models were compared to the results of other proposed models in the current literature.

We are able to infer from the above-mentioned studies that the fuzzy-logic-based model gives the most realistic results. We believe that since the fuzzy-logic-based model has a physical base, its accuracy is higher.

XIV. COMPARISON CRITERIA

Here we make another objection to the researchers' evaluation criteria. Many authors indicated that a high correlation coefficient between the model results and the real data confirms their model's high accuracy. However, we postulate that having a high correlation coefficient between the model results and the real data only shows that there is a strong statistical dependency between them. We insist that the Pearson correlation coefficient or determination coefficient between the two series, like 1, 2, 3, 4 and 10^6, $2*10^6$, $3*10^6$, $4*10^6$ is one. Let us assume that the first series is composed of real data and the second one is the model result. The model estimates are therefore one million times greater than the real data when the Pearson correlation coefficient is one. On the other hand, closely related statistical magnitudes (average, max, min, and s. deviation, etc.) are not enough to ensure that a model is successful. Therefore, to ensure that a model is indeed successful, we suggest that using as many comparison criteria as possible is better than using a small number of comparison criteria. Toprak (2004) [4], Toprak et al. (2004a), Toprak et al (2004b) [6-7], Toprak and Savci (2007), and Toprak and Cigizoglu (2008) [9-10] claim that the comparison should be made at least by considering: 1) seven statistical magnitudes (maximum, minimum, average, standard deviation, skewness, variation, and correlation coefficients), 2) three or more different error criteria (i.e. mean square error MSE, standard error SE, and normalized error NE), and 3) contour map method. The investigations done in the works we have discussed have shown that the contour map method is suitable for comparing different results against each other and/or against any available database.

XV. CONCLUSIONS AND RECOMMENDATIONS

In this study, we have offered a large-scale and critical review of existing literature on LDC. We derive the following conclusions from our findings:

1) Although it is well known that equations that use dimensionless LDC have more generality than equations that use dimensional LDC, there are not enough proposed models to estimate the dimensionless LDC directly. Therefore, we still need further models to estimate dimensionless LDC in natural channels.

2) Almost all modeling techniques (i.e. regression analysis and many other statistical analyses) require several pre-conditions before they can be used. Researchers tend not to take such pre-conditions into account when developing a model.

3) Toprak et al. (2004b) [7] is offered to study the comparison among models and real data sets.

4) The ANN, geno-fuzzy, and neuro-fuzzy based models can be categorized in the class of black-box models. Such models have high accuracy, but since they have no physical base (just like regression analysis based models are not based on physical laws), they need reliable data for modeling and they must be re-modified against different data. On the other hand, fuzzy-logic-based models have more physical base and offer more precise results.

5) Works that comparatively review all published studies on both dimensional and dimensionless LDC are still needed.

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